Extent and ecosystem impacts of Biological Soil Crust in the Colorado River Basin

Steve Fick

Abstract

On the Colorado Plateau, the main watershed for the Colorado River, mat-forming associations of mosses, lichens, fungi and cyanobacteria known as Biological Soil Crusts (BSC) cover an extensive amount of soil surface. BSC are known to provide critical services for this ecosystem, such as stabilization of soil surfaces against wind and water erosion, addition of biologically fixed N and C to low-fertility soils, and provision of microsites for vascular plant establishment. However BSC are particularly vulnerable to mechanical disturbance by humans, for which recovery times may be slow. This paper examines the ways that global change in the form of altered climate and increased human presence in the region affect BSC, and how these impacts may lead to changes in water supply and quality in the Colorado River. It is suggested that direct disturbance of BSC by increased human visitation to the region is the primary threat to BSC, followed by losses due to climate change related to alterations in precipitation timing and frequency. There is reason to believe that heightened erosion due to loss of BSC has resulted in changes of alpine snowpack albedo and runoff to the Colorado River, as well as changes in sediment and nutrient loading to lower tributaries. However, more information is needed to establish the magnitude to which BSC disturbance is responsible for these effects.

Goals of the Paper

- Briefly review the literature discussing the structure and function of BSC in arid environments, such as the Colorado Plateau. Particular attention will be given to features of BSC that may especially vulnerable to global change or have 'downstream' impacts on the Colorado River.
- Discuss how global change in the form of altered climate and increased human population in the Colorado Plateau may impact BSC, drawing on projected changes for the region and experimental evidence for impacts on crusts.
- Relate changes in BSC communities to potential broader scale impacts on the Colorado River basin hydrology and function.

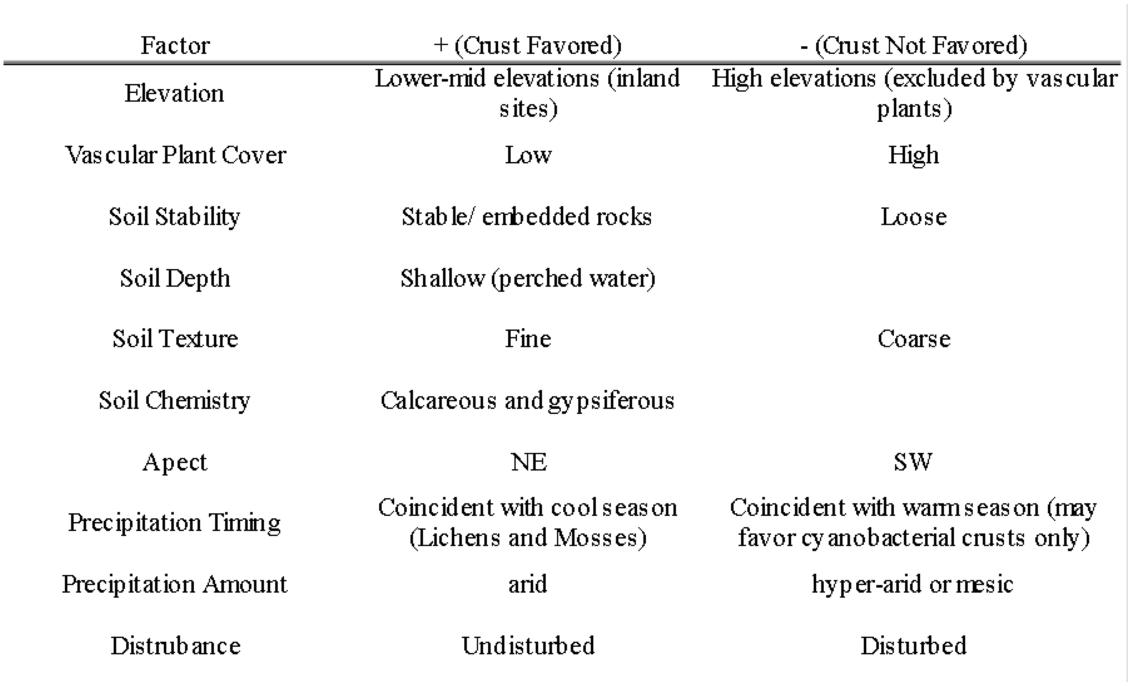
Literature Synthesis

Structure and Function

Biological Soil Crusts (BSC) are mat-forming associations of lichen, moss, fungi and cyanobacteria that grow on the soil surface and provide important regulatory services in many ecosystems (de Groot et al. 2002, Elbert et al. 2012). Although they are found throughout the world often in early successional habitats, BSC may be particularly prevalent in arid regions, where soils, climate, and limited vascular plant cover may permit persistence (Belnap et al. 2001a; See Table 1). On the Colorado Plateau, the main watershed for the Colorado River, BSC are common, and cover large areal extents of soils within the region. Here, they form distinctive dark-colored pinnacled surfaces which may totally cover the soil surface in plant interspaces (see figure 1).

Figure 1: Biological Soil Crusts (BSC) form dense, pinnacled mats in plant interspaces across the Colorado Plateau, the major watershed for the Colorado River

Numerous studies indicate that BSC are important functional components of ecosystems on the Colorado Plateau, regulating patterns of vascular plant establishment as well as fluxes of dust, C, N, and water. Because of their physically rough pinnacled surface, BSC provide microsites for wind-blown vascular plant propagules, and the presence of BSC has been linked with reduced cover of invasive annual grass *Bromus tectorum,* suggesting that crust influence on plant establishment may be species-specific (Belnap et al. 2001b). BSC also contribute significant amounts of fixed atmospheric C and N to low-fertility soils, around 52 kg*ha-1*yr-1 C (representing ~4% NPP) and 7.6 kg*ha-1*yr-1 N (Elbert et al. 2012). In lichen-dominated crusts N fixation may reach up to 13 kg*ha-1*yr-1(Belnap 2002). BSC furthermore influence local patterns of water infiltration, and hence larger-scale patterns of surface-runoff from precipitation events (Belnap et al. 2005). However, the effect of BSC on infiltration vary by context and levels of crust development; in some cases BSC increase infiltration and in other cases they reduce it (Belnap et al. 2001a). Perhaps most importantly, BSC mats are highly resistant to wind and water erosion and thus help retain soils and reduce atmospheric dust emissions. In comparison with bare soils, well developed BSC have an approximately 4-fold increase in threshold friction velocity the minimum wind velocity needed to elicit particle movement (Belnap and Gillette 1998; see fig 2).



Factor	+ (Crust Favored)	- (Crust Not Favored)
Elevation	Lower-mid elevations (inland sites)	High elevations (excluded by vascular plants)
Vascular Plant Cover	Low	High
Soil Stability	Stable/ embedded rocks	Loose
Soil Depth	Shallow (perched water)	
Soil Texture	Fine	Coarse
Soil Chemistry	Calcareous and gypsiferous	
Apect	NE	SW
Precipitation Timing	Coincident with cool season (Lichens and Mosses)	Coincident with warm season (may favor cyanobacterial crusts only)
Precipitation Amount	arid	hyper-arid or mesic
Distrubance	Undisturbed	Disturbed

Table 1: Environmental controls on BSC distribution and abundance in arid ecosystems. From Belnap et al. 2001a.

Impacts of Global Change on BSC

While intact crusts are highly resistant to wind and water erosion, they are particularly vulnerable to mechanical disturbance by foot-traffic, livestock grazing, and off-road vehicle use (Garcia-Pichel and Belnap 1996, Belnap and Gillette 1998). Once crushed or buried, BSC are unable to provide key ecosystem services such as resistance to erosion or N fixation (Belnap and Gillette 1998, Evans and Belnap 1999). Moreover, recovery times following disturbance are variable, but may require 15-100 years in order to regain full function (Belnap et al. 2001a). Losses of BSC in combination with damage to perennial vegetation and invasion by exotic annuals may result in a feedback between accelerated loss of soil resources and declines in system productivity. In Canyonlands National Park, which lies in the heart of the Colorado Plateau, records indicate that by the time the park was established in 1974, grazing allotments could only support ~50 % the stocking density reported in the early 20th century(National Park Service, Rocky Mountain region 1974). Today, despite the fact that the park has excluded livestock grazing for nearly 40 years, there is evidence that many areas remain in persistent states of degredation, marked by extensive bare soil, dominance by invasive exotic annuals, and minimal BSC recovery (Miller et al. 2011).

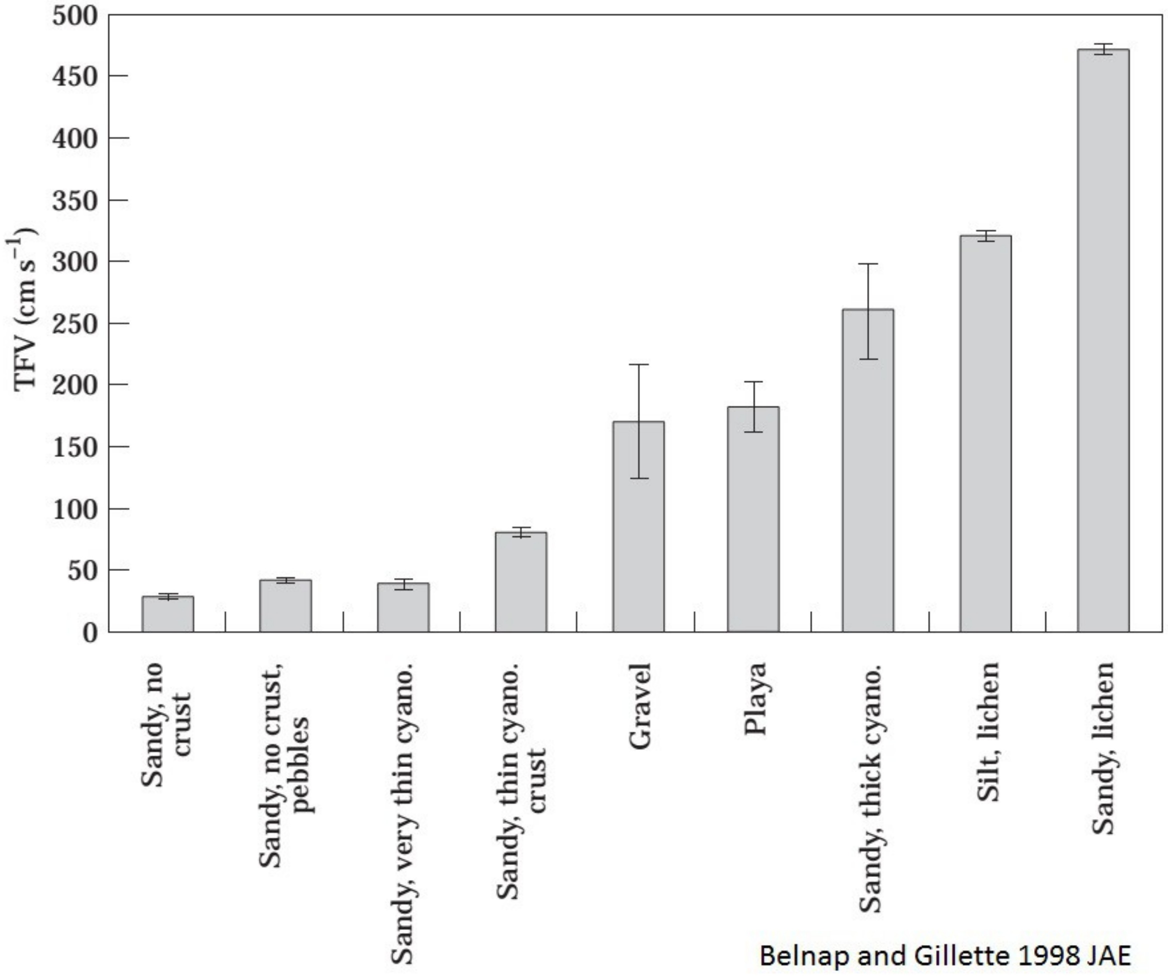


Fig 2: From Belnap and Gillete 1998. Relationship between experimental disturbance of BSC and Threshold Friction Velocity (TFV) measured by a wind tunnel in the field. TFV is a measure of resistance to wind erosion.

Although the vulnerability of crusts to human disturbance is well documented and efforts have been made to reduce human impacts on BSC, historical land use patterns and current population pressure continue to challenge the integrity of BSC throughout the Colorado Plateau. Since the 19th century, both grazing and extractive mining have been the dominant sources of income for the region, each having substantial impacts on soil surface and BSC disturbance(Schwinning et al. 2008). In contrast to native ungulate browsers of the region, which lightly impact BSC, grazers such cattle and sheep can trample large areal extents of the soil surface. Similarly mining necessitates the construction of roads and use of heavy equimpment which compacts and disturbs soils. Today, population growth in the West (predominantly urban) and economic concomitant changes have resulted in the emergence of a significant service and recreation-based component of the local economy(Schwinning et al. 2008), resulting in mixed effects for the status of BSC in the region. On the one hand, higher visitation rates by humans to the area, especially in off-road vehicles have negative impacts on BSC, often in remote and previously undisturbed habitats. However, activities related to the service and recreation based economies do not necessitate disturbance of soils *per se,* and often raise awareness for and even incentivize protection and restoration of areas covered with BSC. Nevertheless, the economies of the region have been historically vulnerable to external fluctuations in the global economy(Schwinning et al. 2008), and as such there is considerable uncertainty regarding the continued role of tourism, mining and ranching in the region.

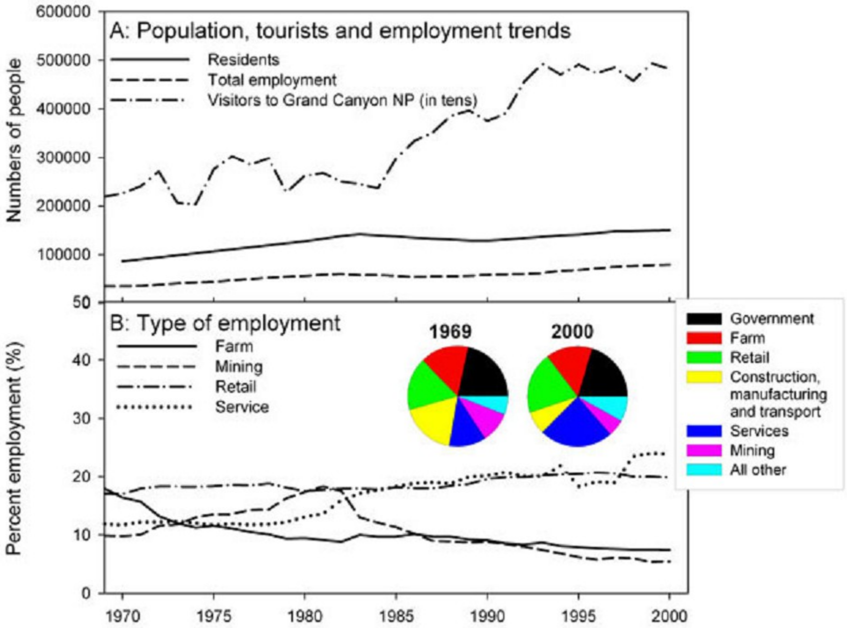


Fig 3: From Schwinning et al 2008. Trends in population and employment in the Colorado Plateau from 1969 -2000, highlighting increased, population size, recreational visitation, and growth of a service industry

In addition to challenges from increasing human presence in the landscape, global climate change will also likely impact BSC and related communities. Projections for climate change in the region generally predict drier conditions overall, with increase frequency of extreme droughts and hot summers (Christensen et al. 2004, Cayan et al. 2010). On a regional scale, the distribution and composition of BSC are correlated with both precipitation and temperature (Belnap et al. 2001a), thus changes in these variables may favor certain groups within BSC communities over others. BSC are poikilohydrophilic, meaning that they are only metabolically active when moisture is available, and reactivation following a dry state is costly in terms of C and N (Schimel et al. 2007). Thus variation in regional distributions of BSC types may be partially explained by varying abilities within BSC taxa to achieve a positive C balance after wet-up. Laboratory experiments have shown that short durations of exposure to moisture can result in negative C balance for certain BSC taxa (Jeffries et al. 1993). Similar results have been achieved in the field via experimental manipulations of water simulating small, frequent precipitation events. Belnap et al.(2004) found reduced photosynthetic performance and reduced production of UV protective pigments in BSC under these conditions, but only during the summer months. Similarly Reed et al. (2012)found that the moss *Syntrichia caninervis*, a common member of BSC on the Colorado Plateau, was nearly extirpated following short and frequent precipitation additions during the summer. Subsequent labaratory analysis indicated that water additions equivalent to 1.25 mm rain events resulted in a negative C balance for the species, while 5 mm additions resulted in positive C balance.

In contrast to the effects of alteration in precipitation, the study by Reed et al. (2012) did not find a significant effect of an experimental warming treatment on BSC survival. This follows the general paradigm that the availabilty water is the dominant control on the distribution and function of organisms in arid lands (Noy-Meir 1973). It is likely that the heightened impact of altered preciptation during the hot summer months in both of the aforementioned studies may be explained by reduced residence time of water on the soil surface driven by increased evapotranspiration (Belnap et al. 2004, Reed et al. 2012). In any case, changes in either precipitation or temperature related to climate shifts in the region may be detrimental to some BSC taxa, although more studies are needed to predict the magnitude and species specificity of this response. Compared to the known impacts of human disturbance on crust function, it is difficult to determine how climate change will affect BSC, especially given uncertainty in projections. Currently data suggest that crust function will primarily be impaired in this region under conditions of increased frequency of low intensity precipitation events in summer.

Impacts of BSC on the Colorado River Watershed

Because BSC cover an extensive area of the Colorado River watershed and also mediate local patterns of water infiltration and runoff, erosion and fixed N inputs, it is proposed that BSC may influence the amount of runoff, sediment yield and water-borne nutrients to the Colorado River. Disturbance of BSC can lead to increased erosion of sediment by water (Belnap et al. 2001a), which increases the amount of sediment transported by the river's ephemeral tributaries during storms. This effect may be enhanced by more intense precipitation events related to climate change, leading to reach-level changes in river morphology and ecology(Goode et al. 2012, Siegfried 2014). Nitrogen inputs from BSC fixation can lead to additional N transported to the river, although more tributary-specific information is needed to quantify the magnitude of N from these biological sources relative to N from other sources in the basin (Paulson and Baker 1980).

Loss of BSC in the Colorado River basin, accompanied by heightened wind erosion and emission of dust into the atmosphere may impacts on the timing and amount of runoff water distributed to the Colorado River via alteration of snowpack dynamics in the surrounding mountains. When soils devoid of BSC are eroded by wind, most sediment is transported horizontally across the surface, however a fraction of sediment is emitted into the atmosphere as fine particulate dust (Gillette 1978). This dust may land on snowpack surfaces in the Rocky Mountains and San Juan mountains which lie directly downwind of the Colorado Plateau. In an examination of sediment cores of alpine lakes these mountains, Neff et al. (2008) found a evidence of a nine-fold increase in the deposition of mineral aerosol dust derived from wind erosion of surface soils, related to western settlement of the United States in the 19th century. Sediment-derived dust deposition on snowpack in the San Juan mountains has been found to decrease the albedo of the snow, increasing the amount of radiative energy absorption and shortening the snowpack duration by 18-35 days (Painter et al. 2007). The potential effects of this deposition on runoff to the Colorado River were modeled by Painter et al. (2010), who estimated an effective loss of ~ 5% of water to the Colorado River as a result of earlier exposure of soils and vegetation to evapotranspiration.

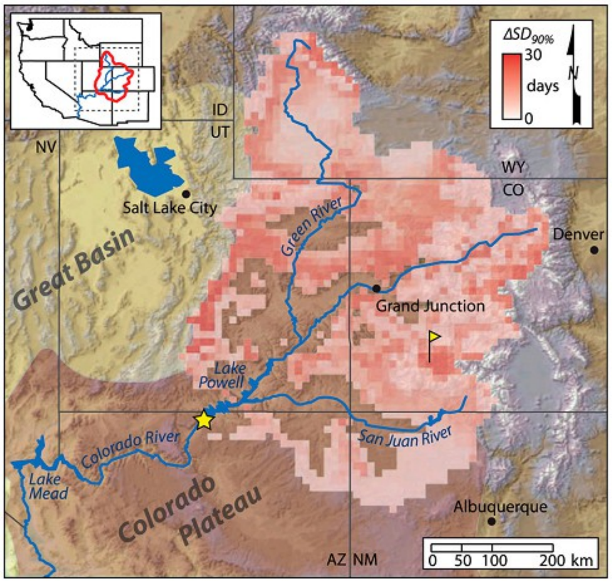


Fig 4: Modeled changes in date for snow melt (delta SD) for the Colorado Plateau due to albedo changes from anthropogenic dust. From Painter et al 2010

Conclusions

- Biological Soil Crusts are important components of both the upper and lower Colorado River watershed which serve to regulate transfers of dust, water, N, C and plant propagules within the landscape.
- BSC are particularly vulnerable to human disturbance, and increased human visitation and population growth in the region may place additional pressures on crust integrity. However there is some hope that as the region's economy shifts to service and tourism base, other extractive livelihoods may become less feasible and crust protection may receive higher management priority.
- Effects of the hotter, drier projected climate scenario for the region on BSC are unclear, however experiments suggests that increases in the frequency of low-intensity warm-season rainfall may cause some BSC community members to perish due to negative C budgets.
- Reductions in BSC undoubtedly have impacts on erosion and inputs of water, sediment, and nutrients to the Colorado River, however more data are needed to determine the relative magnitudes and controls on these inputs.
- Dust emissions linked with BSC and soil surface disturbance are likely causing decreases in snowpack albedo and concomitant changes to the timing and net inputs of runoff water to the Colorado River from mountain-ranges directly down wind of the Colorado Plateau. Overall reductions in inputs have been estimated at ~5%.

Literature Cited

Belnap, J. 2002. Nitrogen fixation in biological soil crusts from southeast Utah, USA. Biology and Fertility of Soils 35:128–135.

Belnap, J., and D. Gillette. 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. Journal of Arid Environments 39:133–142.

Belnap, J., J. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001a. Biological Soil Crusts: Ecology and Management. US Department of the Interior, Bureau of Land Management.

Belnap, J., S. L. Phillips, and M. E. Miller. 2004. Response of desert biological soil crusts to alterations in precipitation frequency. Oecologia 141:306–316.

Belnap, J., R. Prasse, and K. T. Harper. 2001b. Influence of biological soil crusts on soil environments and vascular plants. Biological soil crusts: Structure, function, and management:281–300.

Belnap, J., J. R. Welter, N. B. Grimm, N. Barger, and J. A. Ludwig. 2005. Linkages between microbial and hydrologic processes in arid and semiarid watersheds. Ecology 86:298–307.

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov. 2010. Future dryness in the southwest US and the hydrology of the early 21st century drought. Proceedings of the National Academy of Sciences 107:21271–21276.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer. 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change 62:337–363.

Elbert, W., B. Weber, S. Burrows, J. Steinkamp, B. Büdel, M. O. Andreae, and U. Pöschl. 2012. Contribution of cryptogamic covers to the global cycles of carbon and nitrogen. Nature Geoscience 5:459–462.

Evans, R. D., and J. Belnap. 1999. Long-term consequences of disturbance on nitrogen dynamics in an arid ecosystem. Ecology 80:150–160.

Garcia-Pichel, F., and J. Belnap. 1996. Microenvironments and Microscale Productivity of Cyanobacterial Desert Crusts1. Journal of Phycology 32:774–782.

Gillette, D. 1978. A wind tunnel simulation of the erosion of soil: Effect of soil texture, sandblasting, wind speed, and soil consolidation on dust production. Atmospheric Environment (1967) 12:1735–1743.

Goode, J. R., C. H. Luce, and J. M. Buffington. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology 139:1–15.

De Groot, R. S., M. A. Wilson, and R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41:393–408.

Jeffries, D. L., S. O. Link, and J. M. Klopatek. 1993. CO2 fluxes of cryptogamic crusts. New Phytologist 125:163–173.

Miller, M. E., R. T. Belote, M. A. Bowker, and S. L. Garman. 2011. Alternative states of a semiarid grassland ecosystem: implications for ecosystem services. Ecosphere 2:art55.

National Park Service, Rocky Mountain region. 1974. Environmental Assessment; Proposed Grazing Phase-Out at Canyonlands National Park, Utah.

Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds. 2008. Increasing eolian dust deposition in the western United States linked to human activity. Nature Geoscience 1:189–195.

Noy-Meir, I. 1973. Desert Ecosystems: Environment and Producers. Annual Review of Ecology and Systematics 4:25–51.

Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride, and G. L. Farmer. 2007. Impact of disturbed desert soils on duration of mountain snow cover. Geophysical Research Letters 34.

Painter, T. H., J. S. Deems, J. Belnap, A. F. Hamlet, C. C. Landry, and B. Udall. 2010. Response of Colorado River runoff to dust radiative forcing in snow. Proceedings of the National Academy of Sciences 107:17125 –17130.

Paulson, L. J., and J. R. Baker. 1980. Nutrient interactions among reservoirs on the Colorado River.

Reed, S. C., K. K. Coe, J. P. Sparks, D. C. Housman, T. J. Zelikova, and J. Belnap. 2012. Changes to dryland rainfall result in rapid moss mortality and altered soil fertility. Nature Climate Change 2:752–755.

Schimel, J., T. C. Balser, and M. Wallenstein. 2007. Microbial stress-response physiology and its implications for ecosystem function. Ecology 88:1386–1394.

Schwinning, S., J. Belnap, D. R. Bowling, and J. R. Ehleringer. 2008. Sensitivity of the Colorado Plateau to change: climate, ecosystems, and society. Ecology and Society 13:28.

Siegfried, L. 2014. Sediment Supply and Flow in the Colorado River Basin. UC Davis 2014 Grand Canyon River Course.