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Original Research

Insights from Long-Term Ungrazed and Grazed Watersheds in a Salt Desert Colorado Plateau Ecosystem☆

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ABSTRACT

Dryland ecosystems cover over 41% of the earth's land surface, and living within these important ecosystems are approximately 2 billion people, a large proportion of whom are subsistence agropastoralists. Improper grazing in drylands can negatively impact ecosystem productivity, soil conservation, hydrologic processes, downstream water quantity and quality, and ultimately human health and economic well-being. Concerns regarding the degraded state of western US rangelands in the 1950s resulted in an interagency committee to study the effects of land use on runoff and erosion processes. In 1953, a federal research group established four paired watersheds in western Colorado to study the interaction of grazing by domestic livestock, runoff, and sediment yield. Exclusion of livestock from half of the watersheds dramatically reduced runoff and sediment yield after the first 10 yr—primarily due to changes in ground cover but not vegetation. Here, we report results of repeated soils and vegetation assessments of the experimental watersheds after more than 50 yr of grazing exclusion. Results show that many of the differences in soil conditions between grazed and ungrazed watersheds observed in the 1950s and 1960s were still present in 2004, despite reduced numbers of livestock: few differences in vegetation cover but large differences in biological soil crusts, soil stability, soil compaction, and soil biogeochemistry. There were differences among soil types in response to grazing history, especially soil lichen cover and soil organic matter, nitrogen, and sodium. Comparisons of ground cover measured in 2004 with those measured in 1953, 1966, and 1972 suggest much of the differences between grazed and ungrazed watersheds likely were driven by high sheep numbers during droughts in the 1950s. Persistence of these differences, despite large reductions in stocking rates, suggest the combination of overgrazing and drought may have pushed these salt desert ecosystems into a persistent, degraded ecological state.

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Introduction

Arid and semiarid ecosystems (drylands hereafter) cover >41% of Earth's land surface, and approximately 2 billion people live within these important ecosystems (Millennium Ecosystem Assessment, 2005). Drylands are defined by water scarcity, and concerns regarding how land-use activities may modify ecosystem productivity and hydrologic processes are paramount (Noy-Meir, 1973). Grazing by domestic livestock is the most widespread land use in drylands globally, and a large proportion of dryland residents can be characterized as subsistence agropastoralists (Millennium Ecosystem Assessment, 2005; Steinfeld et al., 2006). Improper grazing in drylands can negatively impact ecosystem productivity, soil conservation, hydrologic processes, and downstream water quantity and quality. Of particular concern are potentially irreversible ecosystem state changes brought about by improper grazing on sensitive soils and plant communities (often referred to as "desertification"; Schlesinger et al., 1990; Bestelmeyer et al., 2015).

Grazing by large domestic herbivores affects dryland ecosystems directly through selective removal of plant biomass and physical disturbance (hoof impact) and indirectly via feedbacks with other ecosystem processes (e.g., plant competition, plant-soil feedbacks). Herbivory generally reduces overall vegetative cover and can alter vegetation composition through changes in plant competitive relationships (e.g., favoring unpalatable species) and introduction of invasive species (Fleischner, 1994). The physical effects of hoof action on soils can break up physical and biological soil crusts, increase soil erodibility, compact subsoils, and create preferential hill slope flow paths resulting in increased gully formation (due to animal trailing; Branson et al., 1981; Warren et al., 1986). Furthermore, the direct effects of grazing—especially overgrazing—on plants and soils can disrupt or alter dryland ecosystem processes and result in

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profound, often irreversible, changes. For example, heavy grazing coupled with introduction of invasive shrubs resulted in long-term state change in Chihuahuan Desert grasslands even after many decades of rest from livestock (Schlesinger et al., 1990; Yao et al., 2006; Bestelmeyer et al., 2011). These concerns are especially salient given the increasing risk of multiyear droughts due to climate change (Cook et al., 2015) and the demonstrated low resilience of many sensitive dryland ecosystems to the combined impacts of grazing and drought.

Concerns regarding the persistent degraded state of many western US rangelands and the impact of those degraded systems on hydrologically connected streams and reservoirs led to the establishment of an interagency committee in the 1950s to study the effects of land use (primarily grazing by domestic livestock) on runoff and erosion processes (Lusby et al., 1964). In 1953 the Sedimentation Subcommittee of the Pacific Southwest Interagency Committee selected the Badger Wash basin in western Colorado as a focus area to study the interaction of land use, runoff, and sediment yield. Badger Wash was selected because it was broadly representative of rangeland conditions on much of the Colorado Plateau, and the topography facilitated measurement of catchment scale hydrology. Lusby et al. (1964) established a network of four paired watersheds with domestic livestock excluded from one watershed in each pair. The effects of excluding domestic livestock on runoff and erosion processes were dramatic—runoff was ~30% and sediment yield ~45% less in the ungrazed than grazed watersheds after only 3 yr (Lusby, 1970). A surprising result was that these relatively rapid changes in runoff and sediment yield were not accompanied by systematic changes in vascular vegetative composition or cover. A more detailed evaluation of vegetation and ground cover changes after 10 yr by Turner (1971) still detected only relatively small differences in vascular vegetative cover between grazed and ungrazed watersheds; these results were also observed in other salt desert ecosystems in the region (Alzerreca-Angelo et al., 1998). The primary changes attributable to grazing history were related to soil surface attributes (moss, litter, bare ground, and rock cover; Branson and Owen, 1970; Lusby, 1970; Turner, 1971).

A component of dryland ecosystems that was not well understood at the time of the original Badger Wash work is the diverse community of cyanobacteria, mosses, and lichens that often occupy exposed soil surfaces (Marble and Harper, 1989; Lange and Belnap, 2016; Weber et al., 2016). Biological soil crusts (BSCs) are found in most of the world's drylands and, when intact, play an important role in several critical dryland ecosystem processes (Belnap et al., 2016; Weber et al., 2016). They influence vulnerability to wind and water erosion (Belnap and Büdel, 2016), local and regional hydrologic cycles (Belnap, 2006; Painter et al., 2010; Chamizo et al., 2016), nutrient and carbon cycles (Barger et al., 2016; Sancho et al., 2016), and the establishment of vascular plants (e.g., Zhang and Belnap, 2015). Because the degree to which they perform these functions depends on their successional stage, disturbance can have severely disruptive effects (Belnap and Eldridge, 2003). Given the importance of BSCs in drylands globally (Weber et al., 2016) and in the Colorado Plateau in particular (Belnap and Gardner, 1993), it is likely that the differences in runoff and erosion between grazed and ungrazed pastures in the early work can be attributed to differences in BSC intactness (in addition to the mosses that were recorded).

Although no follow-up research on the Badger Wash study area has been published since the 1970s, the livestock exclosure fences have been maintained and the study area remains a valuable opportunity to evaluate ecological patterns and processes in watersheds with contrasting grazing histories. To provide further information on management of grazing in drylands, we report here results of soils and vegetation assessment of the experimental watersheds in the Badger Wash study area after more than 50 yr of grazing exclusion. We repeated vegetation and ground cover measurements and attempted to repeat the runoff and erosion measurements done by Lusby (1979). However, due to a combination of drought conditions and sedimentation of the retention ponds used in the original studies, we were unsuccessful in measuring runoff and erosion. Therefore, the specific objectives of this study were to 1) determine impact of grazing history on the vegetation community, BSC, soil physical properties, and soil biogeochemistry; 2) evaluate if grazing history effects vary with soil type; and 3) revisit results of previous vegetation studies in Badger Wash, last evaluated in 1972, to assess long-term ecosystem trajectories.

Methods

Study Area Description

The Badger Wash study area is located in western Colorado, within the Colorado Plateau physiographic province (39.3397 N latitude, 108.9339 W longitude; approximately 1 530 m elevation; Fig. 1**a**). The climate is dry and warm with a mean annual precipitation of 239 mm, mean annual maximum temperature of 19.2°C, and mean annual minimum temperature of 1.3°C (1971–2000 averages; climate data from approximately the same elevation but 27 km southeast in Fruita, Colorado; Western Regional Climate Center, http://www.wrcc.dri.edu). The four paired watersheds, established in 1953, range in size from 4.9 ha (watershed 4B) to 40.9 ha (watershed 2B; see Fig. 1; Lusby, 1979). Topography is generally rolling (slopes < 8°) with the exception of watershed 4, which consists of steeper erosional breaks (slopes > 10°).

Study area soils are derived from Mancos Shale, a late Cretaceous age marine sedimentary formation that occurs throughout the western United States (see Fig. 1a). The Mancos Shale is dominated by fine-textured material deposited in a deep sea basin and is characterized by high amounts of evaporate minerals (Whittig et al., 1982). The Mancos Shale is likely a major contributor of dissolved mineral salts to the Colorado River (Miller et al., 2017). At the western extent of these deposits, including in the Badger Wash area, the fine-textured shale intertongues with coarser-grained, nonsaline sandstones. Lusby et al. (1964) mapped three soil types that have formed in residuum from these contrasting parent materials, along with a fourth alluvial geomorphic surface that occurs between the structural hills and benches (Fig. 1b; Table 1). The sandstone parent materials are more resistant to erosion, and thus soils occur primarily as benches with relatively even and gentle slopes, are distinctly sandier in texture than the other soil types, and are the least alkaline. The shale soils are highly erodible, can be steeply sloping, and are typically the most alkaline and finest in texture. The mixed soil type is the most extensively mapped (Fig. 1b; see Table 1) and is formed from a mixture of sandstones and shales. The alluvial soils occur in the topographic lows and due to the range of alluvial source material encompass a variety of textures and salinity (Lusby et al., 1964).

Vegetation in the Badger Wash study area is typical salt-desert shrub type (Lusby et al., 1964; Alzerreca-Angelo et al., 1998; see Table 1). Stable alluvial soils tend to be dominated by larger shrubs such as *Artemisia tridentata* and *Atriplex confertifolia,* and the active washes are inhabited by *Sarcobatus vermiculatus* and *Chrysothamnus* spp. *Poa secunda* is the most common grass on alluvial soils, and moss cover is generally high. In the mixed soils, *Atriplex confertifolia, Atriplex gardneri, Gutierrezia sarothrae*, and smaller *Eriogonum* (*E. bicolor* and *E. contortum*) shrubs are common. Grasses may be the dominant cover or codominant with shrubs. Sandstone soils typically support *Atriplex confertifolia* and relatively high amounts of perennial grasses (including *Leymus salinus* and *Pleuraphis jamesii*). On the shale soils, *Atriplex gardneri* and *Atriplex corrugata* dominate with sparse cover of perennial grasses. All soils have considerable microtopography due to the presence of mosses and lichens and soil heaving resulting from freeze-thaw cycles.

The Badger Wash study area is administered by the Bureau of Land Management (BLM) and has been actively grazed by domestic livestock since the 1880s (see review by Lusby, 1979). Grazing up through the Taylor Grazing Act (1934) was widespread and heavy. It consisted primarily of migratory domestic sheep moving between winter and summer ranges. The location of a railway shipping point nearby and the