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Integrating precipitation, grazing, past effects and interactions in long-term vegetation change

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A B S T R A C T

Determining the causes of vegetation change in arid and semi-arid environments can be difficult and may involve multiple factors, including disturbance, inter-annual climatic variation, soils, effects from years past and interactions between these factors. Theoretical models describing vegetation change in these systems have generally focused on a single aspect as the primary driver. The integration of these factors into a single model may be what is required to fully understand the drivers of vegetation change in desert systems. To test the contributions of these various factors, we analyzed a long-term (1979–2011) vegetation dataset using multiple linear regression.

While precipitation and livestock density were important variables for explaining vegetation change, the consistency with which past effects and interactions significantly improved the models underscores their importance. Past effects were included in every model except for shrub diversity, and included both precipitation and livestock density effects. A novel approach to addressing the interaction between grazing and precipitation was included by dividing precipitation by stocking density. Grass density had a high positive correlation with this metric, while shrub cover had a small negative correlation. These results support the integration of multiple factors to explain vegetation change.

1. Introduction

Vegetation change in arid and semi-arid ecosystems can be can difficult to understand and can involve complex combinations of, and interactions between, inter-annual climatic variation, soils, disturbance, and effects from previous years. Theoretical models of vegetation change on rangelands have evolved over time from linear (Clements, 1916; Dyksterhuis, 1949) to multi-equilibrial state-and-transition models (Westoby et al., 1989; Laycock, 1991; Briske et al., 2005). Linear succession describes a smooth transition, driven by internal ecosystem processes, such as climate, while the state-and-transition models illustrate discreet states driven by external ecosystem process such as disturbance (Briske et al., 2003). Successional models adapted for rangelands were based on grazing as the driving factor (Briske et al., 2005) and drought was assumed to be additive (Walker, 1993). In other words, the effects of drought could be offset by a reduction in grazing. Additionally, both factors were assumed to temporarily arrest secondary succession (Briske et al., 2003). This approach was found to be inadequate to describe the multitude of states that can occur on a given site, which lead to the development of state-and-transition models (Allen-Diaz and Bartolome, 1998; Bestelmeyer et al., 2003; Briske et al., 2003); however, even as the state-and-transition model was being proposed, it was suggested that a more accurate description may lie somewhere between the extremes of these two models (Westoby et al., 1989). For instance, state-and-transition models focus on disturbance as drivers of change ignoring the contribution of climate and other internal ecosystem factors (Briske et al., 2003). However, inter-annual climatic variation is often considered a controlling factor in vegetation change, even more so than management (Fynn and O'Connor, 2000; West, 2003b; Mashiri et al., 2008). Rare or extreme climatic events can drive change in semi-arid systems (West et al., 1979; Walker, 1993; Holmgren and Scheffer, 2001) or in some cases the convergence of multiple rare events are responsible

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(Wiegand and Milton, 1996).

It has also been suggested that the two competing models may address different temporal scales of change and that the integration of the two is what is necessary to formulate an accurate explanation of rangeland vegetation dynamics (Fuhlendorf et al., 2001; Briske et al., 2003). Change may occur episodically and at varying rates depending on interactions between disturbance, vegetation characteristics and inter-annual climatic variation spanning multiple years (Iglesias and Kothmann, 1997; Fuhlendorf et al., 2001; Curtin, 2002; Perlinski et al., 2014). Multiple studies have shown that the interaction between inter-annual climatic variation and disturbance, or between multiple disturbances, are required to understand vegetation change (Fuhlendorf and Smeins, 1997; West and Yorks, 2002). Previous research has suggested that what is missing to make the conceptual models predictive and applicable to management is the integration of the highly stochastic and variable climate regime that exists in semi-arid regions (Walker, 1993; Wiegand and Milton, 1996; Bestelmeyer et al., 2004; Hardegree and Van Vactor, 2004; Briske et al., 2005; McClaran and Wei, 2014). Another factor that may be important are lag effects (Walker, 1993; Wiegand and Milton, 1996). Lags at short time scales, such as the effect of the previous year's precipitation, have been shown to affect plant diversity (Adler and Levine, 2007), while cover for shrubs and grasses were shown to be correlated with precipitation from two to four years previous (Anderson and Inouye, 2001) and productivity of desert grasses can take 2–4 years to recover to expected levels after drought (Moran et al., 2014).

Most ecological studies last less than six years (Tilman, 1989); yet, on arid and semi-arid rangelands it may take as long as 20–25 years for a site to receive a representative range of precipitation (West, 2003a). Therefore, long-term data are necessary to detect phenomena that would otherwise be beyond the scope of human observation, such as slow, sporadic or rare events (Hobbie et al., 2003). The use of permanent plots is considered a valuable method for this type of temporal analysis (Stohlgren, 2007), though they are a rare resource. Long-term studies which include disturbances are considered key to understanding rangeland systems (Allen-Diaz and Bartolome, 1998). The objective of this study is to investigate the role of both precipitation and grazing, along with their interactions and past effects, with changes in vegetation occurring over a 30-year span of data collected from permanent plots.

2. Methods

2.1. Site description

The Bodie Hills are situated on the California–Nevada border southeast of Bridgeport, CA and north of Mono Lake. Elevations range from 2100 m to 3100 m. Parent materials originate from the Pliocene and are primarily of volcanic origin, including andesite, dacite, rhyolite and welded tuff (O'Neil et al., 1973). Soils consist of sandy, ashy, and gravelly loams with clays and cobbles at depth. Depth to a restrictive layer is generally greater than 200 cm, though in some cases shallow soils can be discerned based on shifts in vegetation type and overall productivity.

Mean temperature for the period from 1965 to 2011 was 3.18 °C, measured at an elevation of 2550 m (WRCC, 2010). Over this time period, mean maximum annual temperature has increased by about 2.1 °C and mean minimum annual temperature has increased by about 0.39 °C (Morris et al., 2014). Average annual precipitation was 323 mm for the period 1965–2011, also measured at an elevation of 2550 m. The majority of precipitation falls as snow during winter months. Over the past 45 years average total precipitation for the water year (Oct.–Sep.) has declined by approximately 44%, while winter (Dec.–Mar.) precipitation has declined by 33% and spring precipitation (Apr.–Jun.) has declined by 24% (Morris et al., 2014).

The majority of the Bodie Hills area is managed by the USDI Bureau of Land Management (BLM) and is organized into four grazing allotments (Aurora Canyon, Bodie Mountain, Mt. Biedeman and Potato Peak) totaling approximately 38,000 ha. Since 1962 California Department of Parks and Recreation has managed approximately 400 ha around the historical town site of Bodie as Bodie State Historic Park. This site was a major mining area from 1875 until the mid-1880's, producing $70 million in gold and silver over the years and hosting a peak population of between 7000–12,000 people in 1880 (Sprague, 2003). Mining activity continued intermittently until World War II, at which point the town was deserted.

Despite the pattern of resource over-exploitation associated with historical mining operations (Young and Budy, 1979; Sprague, 2003), survey records from 1942 describe range conditions in the Bodie Hills area as generally good and “underutilized” (Bell, 1943). BLM records from the late 1950's indicate that the number of sheep animal unit months (AUM) in the Bodie Hills area ranged from 16,000–18,000 (BLM, 1958, 1959, 1960) plus an additional 500–700 cattle AUMs. In 1964 the number of sheep AUMs on the Aurora Canyon, Mt. Biedeman and Potato Peak allotments alone was around 7500, plus an additional 1200 cattle AUMs (BLM, 1964). During the 1960's and 1970's the total number of AUMs decreased and many of the allotments were converted from sheep to cattle grazing. Over the last 30 years, the BLM has continued to reduce stocking rates for both sheep and cattle on all four allotments in the Bodie Hills (Fig. 1; BLM, 2011, 2012). During this time period, sheep have generally been herded within each allotment, while cattle have been allowed to graze freely, from June through October. Adjustments in AUMs were periodically made by the BLM to account for dry years, but the correlation between AUMs and precipitation was low ($R^2 = 0.04$) for current water year and total stocking rate [data not shown]). In addition to domestic livestock, wild grazers and browsers reside in the Bodie Hills (BLM, 2008),

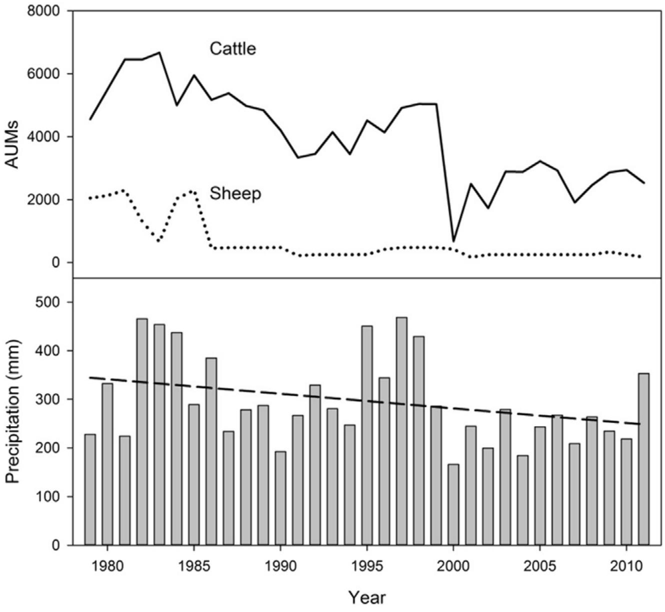

Fig. 1. Changes in livestock numbers and precipitation from 1979 to 2011 in the Bodie Hills, CA. The dashed line in the lower panel shows the trend line for precipitation over this time frame.