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Recent drought phase in a 73-year record at two spatial scales: Implications for livestock production on rangelands in the Southwestern United States

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ABSTRACT

Livestock producers on rangelands are interested in drought at spatial scales of pastures (<25 km^2) and water developments (<14 km^2), and at temporal scales of seasons because summer convective storms are more spatially variable than cyclonic winter storms, and most forage production occurs in summer. Using a 73 y record of monthly precipitation from a dense network of rain gauges (0.1 km^{-2}) and temperature from PRISM we interpolate drought conditions across a large-scale 225 km^2 area in southern Arizona USA, and at a small-scale of 100 separate 1.5 km × 1.5 km cells across the large area. We (1) compared the standardized precipitation index (SPI) and standardized precipitation and evapotranspiration index (SPEI) because the latter includes trends in temperature, (2) calculated the indices for each of the 100 grid cells for winter (Oct–May), summer (Jun–Sep) and water year (Oct–Sep) periods, and (3) compared the most recent 17 y (1996–2012) to the previous 56 y (1940–1995) because drying and warming trends appeared since 1996. We defined drought as the ≤20th percentile, which is the 15 driest years in the 73 y record for each small-scale cell and the large-scale 225 km^2 area. At the large-scale since 1996, temperature increased for all seasons by ~0.9 °C, frequency of water year and winter drought increased >3 fold to 40–65% of years but frequencies did not differ between SPI and SPEI; and the frequency of summer drought did not change after 1996. At the small-scale, the extent of drought increased in winter and water years and decreased in summer since 1996 when using SPEI, but did not change when using SPI. Since 1996, the chances of a management unit-sized drought patch (1–10 contiguous cells) increased in winter, water year, and summer when using SPEI; but not in summer when using SPI. Scaling relationships show extensive drought patches (>20% of large area) when the large-scale is near average conditions, and those patches are larger in summer than winter. Increased drought frequency and patchy spatial distribution of drought have implications for herd structure and herd movements among pastures to avoid economic losses and overgrazing in drought patches. We propose increased efforts to detect drought patches with on-site gauge networks and temperature monitoring as well as remote sensing of precipitation patterns and vegetation indices.

1. Introduction

Drought adversely impacts livestock production on semi-arid rangelands by limiting forage production. Since the late 20th Century, drought has become more common across the Southwestern United States (SW) due to a combination of warming temperatures and precipitation deficits (Seager and Vecchi 2010; Weiss et al., 2009). Spatially, drought conditions are not homogenous at regional- or meso-scales because of variation in the jet stream storm track that delivers winter cyclonic storms and the development of the North American Monsoon which delivers localized summer convective storms (Sheppard et al., 2002; Goodrich et al., 2008). From an operational perspective, livestock producers are most concerned with drought at the spatial scale of the ranch 100–200 km^2, and individual pastures <25 km^2 (Eakin and Conley, 2002; Teegerstrom and Tronstad, 2000). Our work uses a dense network of precipitation gauges (0.1 km^{-2}) to describe the pattern of drought from 1940 to 2012 at these two spatial scales equivalent to a ranch 225 km^2 and individual management units using a

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grid of 2.25 km^2 cells. Our results should encourage efforts to detect drought at the spatial resolution of pasture-size management units, and to develop flexible management practices that can avoid areas of drought within a ranch.

Precipitation deficits are common in the instrumental and proxy records for the SW (Griffin et al., 2013; Herweijer and Seager, 2011), but recent warming in the atmosphere and ocean is linked to circulation patterns that intensified the early 21st Century drought, and is the basis for projections of warming and drying through the 21st Century (Seager and Vecchi 2010). Warming also exacerbated the soil moisture deficits during the recent SW drought beyond that expected from precipitation deficits alone (Weiss et al., 2009). We describe the relative contributions of temperature and precipitation deficits to drought intensity by comparing the records for standardized precipitation index (SPI; McKee et al., 1993) and the standardized precipitation and evapotransporation index (SPEI; Vicente-Serrano et al., 2010) because the latter accounts for temperature-related influences on the soil moisture conditions critical for plant growth on rangelands (Vicente-Serrano et al., 2013). We explore the changes in those indices since 1996 when the combination of warming and drying was detected in the 73-year record.

There is a bi-modal seasonal distribution of precipitation in the SW, with summer (June–September) originating from the North American Monsoon, winter (November–March) originating from cyclonic storms tracking east, and distinct dry conditions between each season (Sheppard et al., 2002). Grass forage production is most sensitive to summer precipitation, but winter precipitation influences plant vigor and potential for growth in the following summer (Cable, 1975; Torell et al., 2011). We describe differences in drought among summer, winter, and water year (October–September) time periods because they have different influences on livestock production and they arise from different climatic mechanisms. For simplicity, we define winter as all non-summer months (October–May) because the dry inter-season months contribute little precipitation and have very limited effect on forage production.

Spatial variation of precipitation is important because livestock operations in the SW require a large area (100–200 km^2) to support an economically viable herd of >250 cows (Teegerstrom and Tronstad, 2000). Under these semi-arid conditions (~200–400 mm y^{-1}), annual forage production is only ~150–250 T km^{-2} (Polley et al., 2013). Ranchers increase forage use efficiency across these extensive areas by establishing drinking water facilities (~0.04–0.08 km^{-2}) and rotating livestock among pastures (<25 km^2). At this spatial scale, summer precipitation originating from small-scale convective mechanisms is more spatially variable than winter precipitation originating from synoptic-scale cyclonic mechanisms. Using a 50-y record from a dense network of gauges across a 150 km^2 watershed, Goodrich et al. (2008) showed that it took 20 y to reach spatial uniformity for summer precipitation but only 10 y for winter. We constructed an interpolated precipitation surface, and applied it to a grid of 1.5 km × 1.5 km cells across a 225 km^2 area to describe the spatial pattern of drought at these scales of operation (1–2 cells ≈ small pasture, 3–6 cells ≈ water development and 7–10 cells ≈ large pasture).

Livestock production on semi-arid rangelands is a very common agricultural practice in the SW, with significant economic impact from cattle sales in 2007 exceeding $1.1 billion for Arizona and New Mexico combined (USDA NASS, 2009). Ranchers are sensitive to problems arising from recurring drought, and are cognizant of spatial variability in the distribution of precipitation (Eakin and Conley, 2002). However, this awareness is not always translated into the design and implementation of management practices. For example, ranchers identified rotation among pastures as the most important practice for responding to drought conditions (Butler, 2012), but those rotations are typically based on calendar dates and predetermined sequences, rather than on conditions emerging from the spatial distribution of precipitation. Without attention to spatial distribution, there is the potential for pastures in drought condition to receive more livestock use than the forage production can support. That situation will reduce livestock production and diminish the capacity for future forage production. Therefore, we describe the frequency of drought patches (contiguous grid cells in drought condition) within the large-scale ranch and the likelihood of drought patches even when the large-scale ranch is not in drought. This information should stimulate efforts to better detect the spatial pattern of drought and to design management strategies that have the flexibility needed to avoid drought patches.

In summary, patterns of drought over the 73-y record of precipitation should (a) be affected by temperature, and the SPI and SPEI indices should differ due to the warming that occurred since the late 20th Century; (b) vary among seasons because of different mechanisms delivering moisture to the SW; and (c) express greater small-scale (2.25 km^2) spatial variability in summer than winter. Therefore, our analytical framework includes comparison of (a) SPI and SPEI indices; (b) winter, summer and water year time periods; and (c) changes since 1996. We apply this framework to describe (1) temporal patterns of drought at the large-scale (225 km^2), (2) the relationship between large- and small-scale drought (extent, patch size and patch number), and (3) the frequency of small-scale drought patch size-classes within the large-scale area.

2. Materials and methods

2.1. Location, data sets, and seasons

The dense network of 22 precipitation gauges is located on the 210 km^2 Santa Rita Experimental Range (SRER) in southern Arizona USA about 50 km south of Tucson, (31°50′ N, 110°53′ W; Fig. 1). Established in 1902, it is the longest continuously active rangeland research area in North America (McClaran et al., 2010). Livestock use has been recorded since 1916 for the 31 pastures which differ in size from 0.9 to 18.5 km^2 (see Livestock Grazing History http://cals.arizona.edu/SRER/data.html). Elevation increases from 900 to 1450 m; with a corresponding increase in annual precipitation from 275 to 450 mm. Since 1940 the area weighted average annual precipitation is 358 mm, with 42% arriving in winter (Oct–May) and 58% in summer (Jun–Sep); and average annual temperature is 18.44 °C.

We use 73 y of monthly precipitation records collected since October 1939 because the 15 gauges recorded since 1922 were not widely distributed (McClaran et al., 2002). We acquired monthly average temperature for the same 73 y from PRISM at 4 km × 4 km resolution (PRISM, 2013). We define winter as Oct–May, summer as Jun–Sep, and water year as Oct–Sep.

2.2. Large- and small-scale estimates based on inter-gauge interpolation and grid cells

We created a continuous surface of monthly precipitation values using inverse distance weighting (IDW), with a power of 1.67 in ArcMap 9.2 (ESRI, 2009). We validated the surface using a jackknife analysis that generated estimates to judge against the known monthly value for each gauge. We found strong predictive values for the continuous surface (r^2 = 0.862, Fig. A.1). We converted the continuous monthly precipitation and temperature surfaces to a single area-weighted value for each 1.5 km × 1.5 km cell in a 100 cell grid encompassing the SRER and immediate surroundings (Fig. 1).