Extensive Droughts in the Conterminous United States during Multiple Centuries

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ABSTRACT: Extensive and severe droughts have substantial effects on water supplies, agriculture, and aquatic ecosystems. To better understand these droughts, we used tree-ring-based reconstructions of the Palmer drought severity index (PDSI) for the period 1475–2017 to examine droughts that covered at least 33\% of the conterminous United States (CONUS). We identified 37 spatially extensive drought events for the CONUS and examined their spatial and temporal patterns. The duration of the extensive drought events ranged from 3 to 12 yr and on average affected 43\% of the CONUS. The recent (2000–08) drought in the southwestern CONUS, often referred to as the turn-of-the-century drought, is likely one of the longest droughts in the CONUS during the past 500 years. A principal components analysis of the PDSI data from 1475 through 2017 resulted in three principal components (PCs) that explain about 48\% of the variability of PDSI and are helpful to understand the temporal and spatial variability of the 37 extensive droughts in the CONUS. Analyses of the relations between the three PCs and well-known climate indices, such as indices of El Niño–Southern Oscillation, indicate statistically significant correlations; however, the correlations do not appear to be large enough (all with an absolute value less than 0.45) to be useful for the development of drought prediction models.

SIGNIFICANCE STATEMENT: To better understand the variability of spatially extensive U.S. droughts through time and across space, we examined tree-ring-based reconstructions of a relative dryness/wetness index for the period 1475–2017. We identified 37 extensive drought events with durations that ranged from 3 to 12 yr and that on average affected 43\% of the conterminous United States. Also, three of the seven longest droughts occurred after 1900. Because associations between indices of climatic conditions and drought are weak, use of climatic indices for predictive models of drought seems tenuous.

KEYWORDS: Drought; Climate variability; Climatology

1. Introduction

One of the concerns related to global warming is the possible intensification of drought events due to changes in the temporal and spatial variability of precipitation and increases in evapotranspiration associated with increased temperatures (Rind et al. 1990; Schubert et al. 2004a,b; Hoerling and Eischeid 2007; Seager et al. 2007a). To monitor changes in drought characteristics (e.g., frequency, duration, and severity) an understanding of past drought events and associated climatic driving forces is needed.

There have been many previous analyses of drought in the conterminous United States (CONUS) based on data from the instrumental period (i.e., since ~1900) (Karl and Koscielny 1982; Diaz 1983; Karl 1983; Namias 1983; McCabe et al. 2004; Andreadis et al. 2005; Ganguli and Ganguly 2016; McCabe et al. 2016). Karl and Koscielny (1982) reported that the instrumental record indicates that droughts appear to last longer for the interior portions of the CONUS than for coastal areas (Karl and Koscielny 1982; Diaz 1983). Also, Andreadis et al. (2005) showed that droughts during the 1930s, 1950s, and 2000s were the most severe droughts in the CONUS since 1900 on the basis of modeled soil moisture and runoff (Andreadis et al. 2005).

Namias (1983) provided detailed analyses of selected droughts in the CONUS and specifically addressed how the causes of drought are forced largely by atmospheric circulation. Namias (1983) wrote that the mechanisms resulting in drought generally involve persistent subsidence of air that results in compressional warming and lowered relative humidity. Consequently, warm-season droughts over the plains of the central CONUS (i.e., the Great Plains) are generally associated with elevated temperatures. Namias (1983) also pointed out that positive atmospheric pressure anomalies over the central plains often are associated with positive atmospheric pressure anomalies in the east-central North Pacific Ocean and negative atmospheric pressure anomalies over the western CONUS coast. Droughts in the eastern CONUS, in contrast, are often produced by different processes. For example, an impactful drought during the 1960s was associated with persistent negative atmospheric pressure anomalies east of the eastern CONUS coast that resulted in anomalous northerly winds causing dry conditions in New England and the mid-Atlantic states (Namias 1983, McCabe and Wolock 2021). These previous analyses indicate that there is not just one cause of drought in the CONUS but a mix of several causes (Namias 1983).

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In a study of meteorological droughts in the CONUS, Ganguli and Ganguly (2016) reported that the spatial coverage of extreme meteorological drought since 2010 has exceeded the extents of the well-known 1930s (the “Dust Bowl” drought) and 1950s droughts. In addition to examinations of droughts during the instrumental period (e.g., Andreadis et al. 2005), there have been analyses of CONUS drought using paleoclimate reconstructions (Woodhouse and Overpeck 1998; Cook et al. 1999; Stahle et al. 2000; Fye et al. 2003; Herweijer et al. 2007; Woodhouse et al. 2009; Cook et al. 2014; Baek et al. 2019; Burgdorf et al. 2019; Erb et al. 2020). A benefit of using paleoclimate reconstructions for drought analyses is that these data are not limited to the instrumental record; use of paleoclimate reconstructions provides a long drought record to analyze (Cook et al. 1999). For example, in an analysis of drought in the CONUS using tree-ring-based reconstructions of the Palmer drought severity index (PDSI), Cook et al. (1999) showed that the 1930s drought was one of the worst CONUS droughts of the twentieth century and also possibly was the worst CONUS drought since 1700.

In another paleoclimate analysis of drought, Woodhouse et al. (2009) identified two primary drought patterns across North America. These drought patterns were determined through T-mode principal components analysis (Richman 1986) of reconstructed PDSI values for the time period 1404 through 2003. One drought pattern reflected the effects of the El Niño–Southern Oscillation on North American hydroclimate, and the other drought pattern indicated an east-to-west dipole. Woodhouse et al. (2009) also reported that these two modes of drought in North America account for 30% of the variability in PDSI for North America.

Cook et al. (2014) performed a comprehensive analysis of spatially extensive CONUS droughts and examined the occurrence of pancontinental droughts back to the year 1000 Common Era (CE) using tree-ring-based reconstructions of PDSI. They pointed out that pancontinental (or extensive) droughts are rare in comparison with regional drought events. They also reported that large drought events likely represent regional events that are driven by local processes rather than by a continental-scale event. Cook et al. (2014) also noted that extensive drought events were linked to well-known modes of climate variability such as the Southern Oscillation (SO), the Pacific decadal oscillation (PDO), and the Atlantic multidecadal oscillation (AMO).

In a more recent study, Burgdorf et al. (2019) examined summer droughts in North America back to 1600 using tree-ring-based drought reconstructions. Using cluster analysis, Burgdorf et al. (2019) identified two main drought patterns: a 1930s-type drought pattern and a 1950s-type drought pattern. Burgdorf et al. (2019) found that the 1930s- and 1950s-type droughts were associated with different patterns of atmospheric pressure anomalies and sea surface temperature anomalies.

Drought duration, severity, and frequency have been the focus of many previous drought analyses (Karl and Koscienly 1982; Diaz 1983; Karl 1983; Andreadis et al. 2005; McCabe et al. 2016). In addition to these drought characteristics, some studies also have included drought spatial extent in their analyses (Andreadis et al. 2005). In this study we use paleoreconstructions to examine spatially extensive drought events in the CONUS during multiple centuries. The objectives of this study are to 1) identify extensive drought events in the CONUS, 2) examine the temporal and spatial variability of extensive droughts, and 3) explore possible climatic drivers of extensive CONUS droughts.

2. Data and methods

a. Reconstructed PDSI

To identify drought events across the CONUS, we use treering reconstructions of summer (June–August) PDSI values (Cook et al. 2010). These reconstructions of summer PDSI are provided on a 0.5° by 0.5° grid resolution for North America and include 3237 grid cells located in the CONUS. Although some of the reconstructed PDSI time series extend back to 0 CE, we use the reconstructions for 1475–2017 because it is during this period that there are complete data for all 3237 grid cells in the CONUS. The PDSI time series were developed using tree-ring reconstructions up through 1978, after which the PDSI values were computed from instrumental data (Cook et al. 2010). The uncertainty of reconstructed PDSI values increases with the age of the chronology (i.e., the farther back in time), in part, because of fewer tree-ring chronologies on which to base the PDSI estimates. Positive values of PDSI indicate wetter-than-average hydroclimatic conditions, and negative values indicate drier-than-average conditions.

One benefit of using PDSI to define drought events is that this index identifies droughts that are driven solely by hydroclimatic variability, rather than including anthropogenic effects such as stream diversions, dams, and water use. For this reason, PDSI has been used in many previous studies to identify drought events (Diaz 1983; Woodhouse and Overpeck 1998; Cook et al. 2004, 2007, 2010; Cook et al. 2014; Burgdorf et al. 2019).

b. Identifying drought events

In our analyses, we used a method similar to that used by Burgdorf et al. (2019) to identify drought events. Following this method, a spatially extensive dry year was characterized by at least 33% of the CONUS indicating a PDSI value less than or equal to −1. Sequences of dry years were used to identify extensive multiyear dry events such that 1) an extensive dry year was required to initiate a drought event and 2) two consecutive years that were not extensive dry years were required to end a drought event. Drought events had to be at least 3 yr in length (not including the two nonextensive drought years that ended the drought event).

c. Additional datasets

To identify possible climatic drivers of drought events, we used monthly indices of climate teleconnections that include Niño-3.4 sea surface temperatures and the Southern Oscillation index (SOI) as indices of El Niño–Southern Oscillation.
(ENSO), the North Atlantic Oscillation index (NAO), the PDO, the Pacific–North American index (PNA), the Arctic Oscillation index (AO), and the AMO. (See the data availability statement at the end of this paper for links to the data sources for each of these indices.)

3. Results

The percentage of the CONUS with a PDSI value less than or equal to $-1$ is highly variable (ranging from 0.03% to 81.09%) (Fig. 1). Using the time series illustrated in Fig. 1 and the rules described earlier that define a drought event, we identified 37 extensive drought events for the CONUS for the years 1475–2017 (Fig. 1). The 37 drought events included 174 years during the period 1475–2017. The drought events ranged in length from 3 to 12 yr with a median length of 5 yr. The longest drought (12 yr) occurred from 1495 to 1506, and the second-longest extensive drought event (9 yr) occurred from 2000 through 2008 (Fig. 1). Seven of the 37 drought events had a duration of 7 yr or more, and 3 of these 7 events occurred after 1900. In contrast to Ganguli and Ganguly (2016) who found that the spatial extent of meteorological droughts in the CONUS after 2010 were greater than during the 1930s and 1950s droughts, our results show that the 1930s and 1950s droughts are still the most spatially extensive droughts of the instrumental record (since ~1900). These dissimilarities are likely due to differences in methods used to identify drought events. Ganguli and Ganguly (2016) examined meteorological drought using the standardized precipitation index on a monthly time scale, whereas we examined drought using summer PDSI and required that drought events have a minimum length of 3 yr and a minimum spatial extent of 33% of the CONUS.

Maps of mean PDSI computed for each of the 37 drought events indicate that the spatial patterns of dry conditions across the CONUS varied substantially (Fig. 2). Some of the drought events are focused on a particular region such as the western CONUS (e.g., 2000–08 drought event; Fig. 2), whereas others cover most of the CONUS (e.g., 1735–37 drought event; Fig. 2). Coats et al. (2015) also noted that individual extensive (or pancontinental) droughts often have different spatial patterns. The mean spatial extent of drought was $\approx 50\%$ for 8 of the 37 drought events. The median mean extent of the drought events was $\sim 43\%$ of the CONUS. The largest mean extent was $\sim 58\%$ of the CONUS (during 1579–1581).

An important question related to these 37 drought events is how often each of the 3237 grid cells was part of each drought event, or in this case had a PDSI value $\leq -1$ for the years within each drought. The sites with the highest frequency of PDSI values $\leq -1$ during the 37 drought events are located from the north-central United States and then eastward (Fig. 3). Another region with a high frequency of years with PDSI values $\leq -1$ during the 37 drought events is in the southeastern CONUS (Fig. 3). These results show that when there has been an extensive drought in the CONUS, these regions have been included in the drought at least 50% of the time. In contrast, the northwestern United States experienced the fewest years with a PDSI value $\leq -1$ during the 37 drought events.
To understand the variability of PDSI across the CONUS and through time, and how this variability is related to the 37 drought events, we performed an S-mode principal components analysis (PCA; Richman 1986) of the PDSI data for the 3237 grid cells for the 1475 through 2017 period. There are many methods to determine the number of principal components (PCs) to retain for analysis, but there is no single accepted method, and different methods often result in different numbers of PCs to retain (Wicklin 2017). For this analysis, we retained PCs that explained at least 10% of the variance in the PDSI dataset. Based on this threshold, three PCs were retained that explain ~48% of the variability in the PDSI data. The first PC (PC1) explained 22% of the variance, and the second and third components (PC2 and PC3) explained 14% and 12% of the variance, respectively. Given that the number of grid cells is greater than the number of cases and that a general rule of thumb for PCA is for the number of cases to exceed the number of variables (in this case grid cells), we performed an additional PCA using every third grid cell in the PDSI data site (1079 grid cells). Using this reduced dataset, the PCA resulted in the same explained variance and score.
time series. This indicates that the PCA computed using the complete PDSI dataset (3237 grid cells) is a robust result.

We also investigated whether to rotate the PCs as has been done in some previous studies (e.g., Herweijer et al. 2007). The unrotated result reliably reflected the variability in PDSI across the CONUS, especially when compared with spatial patterns of PDSI resulting from a cluster analysis of the data (not shown). In addition, by not rotating the PCs, the additional step of subjectively choosing a rotation method was avoided and the overall result was more straightforward.

The loading patterns for PC1, PC2, and PC3 show the spatial patterns of important modes of variability of the PDSI data (Fig. 4). The loadings for a PC specify correlations between the PDSI time series for a site and the component scores for a specific PC. For PC1, the loadings are negative for most of the CONUS, particularly in the western CONUS (Fig. 4a). These negative loadings indicate an inverse relation between PC1 scores and PDSI values for most of the CONUS. When PC1 scores are positive, there likely are low PDSI values across the western CONUS. When PC1 scores are negative, there are high PDSI values across the CONUS. Additionally, the PC1 score time series is highly correlated with the time series of the percent of grid cells with a PDSI value ≤−1 (Fig. 1); the correlation between these time series is 0.89 \((p < 0.01)\).

The loadings for PC2 indicate a west–east dipole with negative loadings across the western CONUS and positive loadings across the eastern CONUS (Fig. 4b). This indicates that positive PC2 scores are related to low PDSI values across the western CONUS and high PDSI values across the eastern CONUS. When PC2 scores are negative, the opposite spatial pattern of PDSI values typically occurs. The west–east dipole for PC2 is consistent with a west–east dipole in CONUS PDSI identified by Woodhouse et al. (2009) that they presented as one of two primary modes of CONUS PDSI variability.

The loadings for PC3 indicate an approximate north–south configuration of PDSI values (Fig. 4c). When PC3 scores are positive, PDSI values are positive across the northern regions of the CONUS, especially the northwestern United States, and PDSI values are negative across the southern regions of the CONUS, especially in the southwest (Fig. 4c). When PC3 scores are negative the configuration of PDSI values switches to a drier-than-average northern CONUS and a wetter-than-average southern CONUS.

The magnitudes of the PC scores indicate the relative strength and sign of the respective loading patterns for each year included in the PCA (Fig. 5). Thus, the magnitude and sign of the scores provide an indication of the location of wet and dry conditions across the CONUS for any given year. Based on this information several important droughts (and...
(Fig. 5a). PC1 scores are positive for years during the 1930s and 1950s droughts in the CONUS and since about 2000 during the turn-of-the-century drought. In addition, PC1 scores are positive during the late sixteenth century when the sixteenth century mega-drought occurred (Stahle et al. 2000). In contrast, PC1 scores are negative during the early twentieth century when much of the southwestern United States was wetter-than-average and flows of the upper Colorado River (one of the most important rivers in the western United States) were higher-than-average.

The PC2 time series also has features that are related to well-known climatic events. For example, the drought in the western CONUS that started around 2000 corresponds to the positive PC2 scores evident since 2000 (Fig. 5b). The increasing positive magnitude of PC2 scores since the 2000 suggests that the PC2 loading pattern (Fig. 5b) has become stronger since 2000. The increase in PC2 suggests drying of the western CONUS and is consistent with a projected drying of the southwestern CONUS suggested by Seager et al. (2007a).

Similar to PC1 and PC2 scores, the recent western CONUS drought is reflected in positive PC3 scores after 2000 (Fig. 5c). Additionally, similar to PC1 scores, negative PC3 scores during the early twentieth century indicate a wet period in the southwestern CONUS during that time frame.

The signs and magnitudes of PC1, PC2, and PC3 were examined in greater detail for the years included in each of the 37 droughts (Fig. 6). During the years included in the 37 drought events, PC1 scores were primarily positive, with positive values for 147 (~84%) of the 174 years included in the 37 drought events (Figs. 6). This result indicates that the...
loading pattern for PC1 (Fig. 6) was an important feature for most of the years included in the 37 drought events.

In contrast, the scores for PC2 during the years included in the 37 droughts were primarily negative, with 106 (~61%) of the years during the 37 droughts having a negative PC2 score (Fig. 6). This result indicates that the inverse of the loading pattern shown in Fig. 4 was an important component of the 37 droughts examined in this study.

The PC3 scores during the years included in the 37 drought events were nearly equally positive (83 years; ~48%) and negative (91 years; ~52%) (Fig. 6).

Student’s t tests were used to test whether the means of the distributions of PC scores for the years during the 37 droughts are different from zero. The t tests indicated that the means of the distributions of PC1 and PC2 scores are significantly different from zero ($p = 2.2 \times 10^{-16}$ for PC1, and $p = 0.00095$ for PC2), whereas the mean of PC3 scores is not statistically different from zero ($p = 0.459$).

b. Correlations with climate indices

Previous studies have indicated connections between CONUS drought and specific patterns of sea surface temperatures and/or atmospheric pressure patterns (Cole et al. 2002, 2007; Fye et al. 2004; Hidalgo 2004; McCabe et al. 2004; Schubert et al. 2004a,b; Seager et al. 2005; Fye et al. 2006; Herweijer et al. 2006, 2007; Seager et al. 2007b; Herweijer and Seager 2008; Feng et al. 2008; Woodhouse et al. 2009; Cook et al. 2014; Hoerling et al. 2014; Seager and Hoerling 2014; Baek et al. 2019). The relations between CONUS drought and sea surface temperatures and/or atmospheric pressure patterns often are represented by climate indices such as Niño-3.4 sea surface temperatures, the PDO, and the AMO. We examined correlations between the PC score time series and time series of various well-known climate indices (averaged for the cool season, warm season, and water year). The time series examined in this analysis included Niño-3.4 sea surface temperatures and the SOI (indices of ENSO), the NAO, the PDO, the PNA, the AO, and the AMO.

Many of the correlations between the PC time series and the time series of climate indices are statistically significant (Table 1). Overall, however, the absolute values of the correlations are small and do not indicate that a substantial portion of the variability in the PC time series is explained by the climate indices.

PC1 scores are significantly correlated with cool-season SOI and AMO, warm-season PNA, PDO, NAO, and AO, and water-year PDO and Niño (Table 1). The significant correlation between PC1 score time series and PDO, SOI, and Niño reflects the effects of the El Niño–Southern Oscillation on CONUS hydroclimate (Woodhouse et al. 2009).

The PC2 score time series is significantly correlated with the cool-season and the water-year NAO and AO ($p < 0.01$). The correlation of PC2 with AO and NAO is consistent with the suggestion by Woodhouse et al. (2009) that the northern annular mode affects the occurrence of drought in the CONUS. Fye et al. (2006) also reported a link between dry and wet periods in the Mississippi River basin and the NAO. The increase in PC2 scores since approximately 2000 also may be an indication of the effects of climate warming in the western CONUS on drought (MacDonald et al. 2008).

The time series of PC3 scores is significantly correlated with cool-season PDO, Niño, NAO, SOI and AMO; the warm-season PDO; and the water-year PDO, Niño, and SOI ($p < 0.01$). The significant correlations between PC3 and PDO, Niño, and SOI indicate a connection between the variability of eastern tropical Pacific Ocean sea surface temperatures and PC3. Several previous studies have indicated that cool tropical Pacific sea surface temperatures are related to drought in the western CONUS (Cole et al. 2002; Fye et al. 2004; Seager et al. 2005; Herweijer et al. 2006; Cook et al. 2007; Seager et al. 2007a,b; Herweijer and Seager 2008; Woodhouse et al. 2009; Cook et al. 2014; Seager and Hoerling 2014; Coats et al. 2015; Parsons et al. 2018; Baek et al. 2019; Parsons and Coats 2019).

Although there are some climate indices that are significantly correlated with the PDSI PCs, the correlations have small absolute values and when squared indicate that only a small amount of variance in any specific PC is explained. It appears that variability in climate, such as that represented by climate indices, only explains a small amount of the variance in CONUS drought. This result is similar to that of Erb et al. (2020) who reported that La Niña conditions only accounted

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<td>PDO</td>
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for ~13% of drought variability in the CONUS. It might be that drought occurrence on a CONUS-wide scale is too complicated to be explained by linear relations to a few climate indices. Additionally, there is a possibility that regional analyses may indicate stronger connections between drought variability and climate than shown for this national-scale analysis. Cook et al. (2014) concluded that pancontinental droughts may not represent a single extensive process, but rather behave as regionally discrete events influenced by specific climate teleconnections and local land surface feedbacks. Cook et al. (2014) further suggest that identified links between well-known modes of climate variability and regional drought events imply possible seasonal predictability of regional drought events. However, extensive droughts also may be influenced to some degree by near-random internal atmospheric variability, which can increase the difficulty of predicting large-area droughts (Hoerling et al. 2014; Seager and Hoerling 2014; Parsons et al. 2018; Erb et al. 2020).

Another factor influencing drought occurrence is global warming. Cook et al. (2014) suggest the possibility that as global warming continues, pancontinental droughts may become more frequent due to widespread warming. Also, extensive CONUS drought may become more likely in the future since climate models project that much of North America will become drier (Seager et al. 2013; Maloney et al. 2014). For future droughts, Coats et al. (2020) performed an analysis of climate model projections of twentieth-century drought over the Northern Hemisphere extratropics. Some of their conclusions are that climate models project increases in drought severity over the Northern Hemisphere extratropics in the future (as indicated by changes in soil moisture) and that droughts largely will increase in duration, but not in spatial extent. Coats et al. (2020) also point out that climate model projections of future drought are limited by biases in the ability of climate models to simulate natural variability and thus underestimate the range of potential future hydroclimatic conditions.

4. Conclusions

Using tree-ring reconstructions of summer (June–August) PDSI for the period 1475–2017, we identified 37 extensive drought events for the CONUS that included 174 years of the period examined. These drought events ranged in length from 3 to 12 yr and on average affected ~43% of the CONUS. The recent turn-of-the-century drought (i.e., 2000–08), which was focused on the southwestern CONUS, was one of the longest droughts of the last 500 years.

Maps of the mean PDSI values for the 37 drought events indicate that the spatial patterns of extensive droughts are highly variable. For the 37 drought events, the regions that experienced drought most often were in the area from the north-central United States and then eastward, and also areas in the southeastern CONUS. Thus, when an extensive drought occurred these areas were affected by the drought during more than 50% of the years.

A PCA of tree-ring-based reconstructions of PDSI for 1475–2017 resulted in three PCs that explain one-half of the variance in the PDSI data. The first PC represented CONUS-wide dry or wet years with a focus over the north-central United States; the second PC reflected a west–east dipole in PDSI conditions; and the third PC indicated north–south differences in PDSI conditions.

When PC1 scores are positive, PDSI values for much of the CONUS are negative. For ~84% of the 174 years included in the 37 extensive drought events, the PC1 scores were positive. This result indicates that this mode of PDSI variability is a strong indicator of likely drought conditions across the CONUS. Whereas PC1 is an indicator of a CONUS-wide tendency for dry or wet years, PC2 and PC3 are indicators of the spatial locations of dry and wet conditions. Increasingly more positive PC2 scores since approximately 2000 are indicative of the drought conditions across the western CONUS since the turn of the century.

In addition, correlations between climate indices and the PC score time series indicate that many of the climate indices are significantly correlated with the PC score time series; however, the absolute magnitudes of the correlations generally are small, indicating that the climate indices do not explain much of the variance in the PC score time series. The modest relations between the climate indices and the PC score time series suggest that there may be some ability to predict the temporal variability of drought based on PC score time series but predicting the spatial pattern of drought is more difficult. Previous research has suggested that much of the variability in drought is related to near-random internal variability of atmospheric circulation, which may make it difficult to predict drought occurrence (Hoerling et al. 2014; Seager and Hoerling 2014; Parsons et al. 2018; Erb et al. 2020).

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