DROUGHT IN THE WESTERN GREAT PLAINS, 1845–56

Impacts and Implications

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A relatively small, but severe and persistent drought occurred in the western Great Plains during the mid-19th century, and may have contributed to the decimation of bison herds.

The environment and culture of the western Great Plains changed significantly over the course of the nineteenth century. While Native Americans were displaced and Euro-American settlers moved across the region, the bison population, which at one time numbered tens of millions (Flores 1991), suffered an astoundingly abrupt decimation. The cause of this near extinction has been hotly debated and attributed to a range of factors that include the impacts of both Native American and Euro-American land use and hunting (Robbins 1999; West 1995, and references within). Drought has been cited as a possible contributing factor as well, but it is difficult to unravel the roles played by each of these factors. In this paper, we describe a mid-nineteenth-century drought in part of the western plains—recorded by tree rings—that appears to have persisted for more than a decade in some parts of this region. We examine evidence for this drought in historical accounts and its contribution to the bison population's demise. We end by discussing the impacts such a drought might have in the future.

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The droughts of the 1930s and 1950s have long served as benchmarks for severe and sustained drought in the United States. Societal and ecological impacts of these droughts were prolonged and well documented. Although the spatial dimensions of the two droughts were different, both had severe impacts on the high plains of Kansas and Colorado (McGregor 1985). While this region is recognized as drought prone (Karl and Koscielny 1982), the limited length of instrumental records (100 yr or less) precludes a full evaluation of the rarity of these droughts. However, paleoclimatic records provide evidence of climate for years prior to the keeping of instrumental records, and can be used to gauge the severity of droughts in the twentieth century as well as for prior centuries. In recent work, two new tree-ring-based hydroclimatic reconstructions have been produced for the eastern half of Colorado: a streamflow reconstruction for the Colorado Front Range (Woodhouse 2001) and a Palmer Drought Severity Index (PDSI; Palmer 1965) reconstruction for eastern Colorado (Woodhouse and Brown 2001; Fig. 1). These recon-

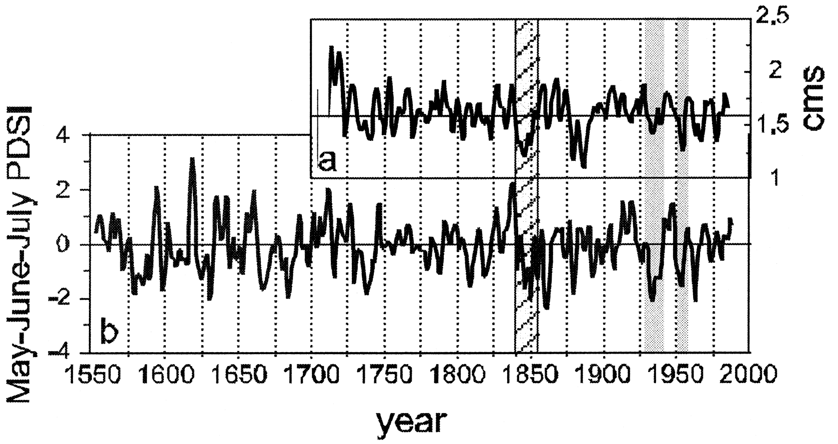

FIG. 1. (a) Reconstruction of Middle Boulder Creek's mean annual flow in (cms) $m^3\ s^{-1}$, 1710–1987 (Woodhouse 2001). (b) Reconstruction of spring/summer droughts (May–Jun–Jul PDSI) for eastern Colorado, 1552–1995 (Woodhouse and Brown 2001). Series have been smoothed with a five-weight binomial filter. The nineteenth-century drought in both series is indicated by the striped bar. The 1930s and 1950s droughts are shaded for comparison of duration and severity to the nineteenth-century drought.

structions indicate a period of remarkably sustained drought and low streamflow lasting from approximately 1845 to 1856 that matched or exceeded the severity of the droughts in this area during the 1930s and 1950s. Another indication of western Great Plains drought about this time is seen in the analysis of tree-ring chronologies flanking the Great Plains (Meko 1992).

This period of drought occurred just prior to the establishment of permanent weather-recording stations in the western Great Plains and thus is not documented in instrumental records. Although there have been a number of tree-ring reconstructions of drought for areas that include the Great Plains, a period of drought as severe and persistent as indicated in the Front Range and eastern Colorado reconstructions is not evident in large regional reconstructions of the central United States (Fritts 1965, 1983; Stockton and Meko 1983; Cook et al. 1996, 1997, 1999; Woodhouse and Overpeck 1998). One reason it has not been recognized in these reconstructions may be an absence of high-resolution paleoclimatic data for the eastern plains of Colorado. For the most part, these past reconstructions utilized trees adjacent to, but not in, the Great Plains to reconstruct climate, a justifiable practice because tree growth typically reflects regional climate variability, and trees suitable for climate reconstructions are rare in the Great Plains. A comparison of a gridpoint reconstruction of drought for eastern Colorado, which is part of a larger reconstruction network, with the more recent eastern Colorado PDSI reconstruction indicates an improved regional reconstruction with the inclusion of Great Plains tree-ring chronologies (Cook et al. 2002; Woodhouse and Brown 2001). Another reason is related to the scale of drought. Studies of large spatial patterns of drought (Cook et al. 1996, 1997, 1999; Woodhouse and Overpeck 1998) indicate discontinuous periods of widespread, severe drought during the 1840s and 1850s. In particular, the years 1845–47 and 1855–56 have been reconstructed as severe drought years for large areas of the western and central United States (Cook et al. 2002), but the persistent drought seen in the new Front Range streamflow and eastern Colorado drought reconstructions is not seen in these large-scale reconstructions. Studies focusing on regional droughts in the eastern and southern Great Plains (Iowa, Arkansas, Texas; Blasing and Duvick 1984; Stahle et al. 1985; Stahle and Cleaveland 1988; Cleaveland and Duvick 1992) do not show severe drought conditions occurring from the mid-1840s to the mid-1850s with the same consistency as seen in the Colorado reconstructions either, suggesting this period of persistent drought was limited in spatial extent. Widespread drought conditions are indicated somewhat later, overlapping with the Colorado drought, in the decade centered around 1860 in reconstructions for the central and southern plains (Fritts 1983; Blasing et al. 1988; Stahle and Cleaveland 1988). In contrast, severe and sustained drought conditions in the Front Range and eastern Colorado abated after 1856 with hydroclimatic conditions remaining near or above average until 1861 (Woodhouse 2001; Woodhouse and Brown 2001).

DEFINING THE DROUGHT. To identify in greater detail the spatial and temporal characteristics of the mid-nineteenth-century drought seen in the two Colorado reconstructions, we examined a set of 60 tree-ring chronologies that range from eastern Montana and western North Dakota, across the western Great Plains/Colorado Front Range to western Colorado, central New Mexico, and Oklahoma, including 11 newly generated tree-ring chronologies from isolated woodlands growing in the western

Great Plains (Woodhouse and Brown 2001; Fig. 2). Annual ring-width values for each of the 60 chronologies were ranked for the 285-yr period, 1680–1964. Rankings were evaluated for 1840–60, the years that bracket the drought documented in the Colorado Front Range streamflow and eastern Colorado drought reconstructions. The years in each chronology that fell within the lowest 50th, 25th, and 10th percentiles of growth were highlighted (Fig. 3). The tree-ring chronology rankings show a core area of low growth that ranges from southern Wyoming to southeastern Colorado/northeastern New Mexico for the years 1845–56 (Figs. 2 and 3). Outside of this region, low growth occurred in subsets of these years in western Colorado (1845–48, 1851), the west/central Dakotas and Nebraska (1845–48, 1855–56), and central New Mexico (1841–43, 1845–48, 1851). In this core area (here called eastern Colorado, but as noted, with extensions into southern Wyoming and northeastern New Mexico), severe drought in 1842 was followed by wet years in 1843 and 1844. The period of sustained drought began in 1845 and was severe and widespread throughout the core region in 1845–48, 1851, and 1855–56. The extent of low growth/drought was less in the intervening years, 1849–50, 1852, and 1854, but smaller core areas of extreme low growth (25th percentile or less) persisted in the northern and central Front Range. The year 1853 was the least severe, with below-median growth persisting only in scattered sites, but with two sites still exhibiting growth below the 25th percentile. By 1857, above-median tree growth returned to many areas, and to virtually all areas by 1858. We interpret this break in widespread low growth in the eastern Colorado region as an end to this period of persistent drought. Below-median tree growth in 1859 indicated a re-

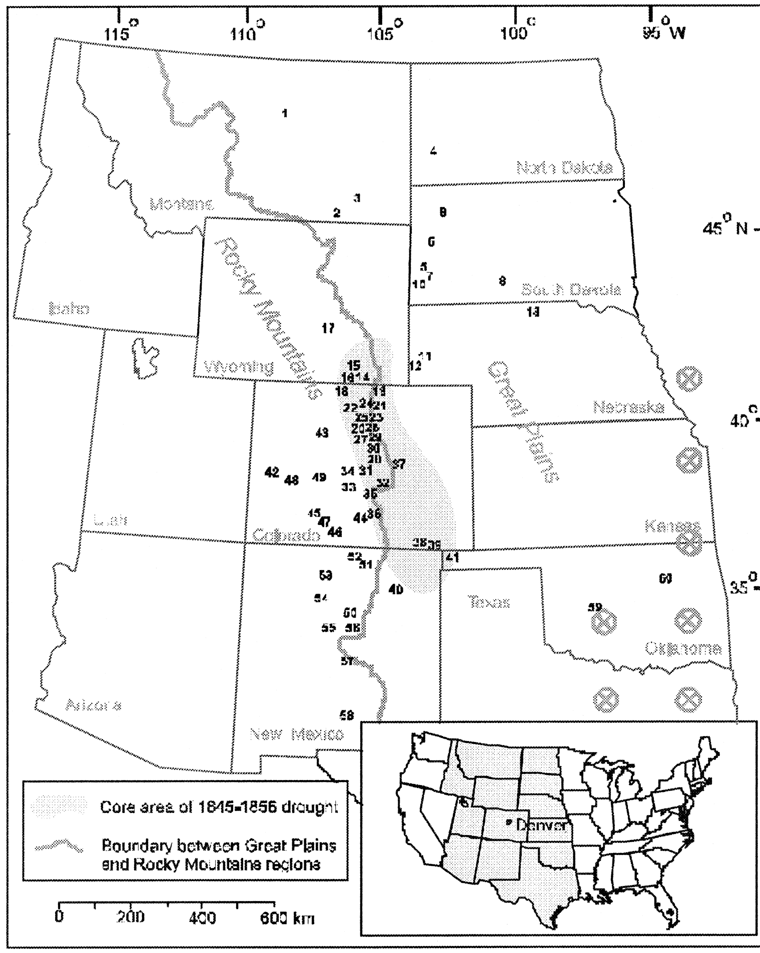

FIG. 2. Locations of tree-ring chronologies. Shaded area indicates core drought region for 1845–56. Chronology sites are numbered and correspond to those listed in Fig. 3. Chronologies selected were from species known to be sensitive to drought (ponderosa pine, *Pinus ponderosa*; Douglas-fir, *Pseudotsuga menziesii*; pinyon pine, *Pinus edulis*; and post oak, *Quercus stellata*), and were taken to be proxies of drought (generally winter/spring in the south grading to spring/early summer in the north). All but the three Montana chronologies (courtesy of D. Meko) were obtained or are now available from the World Data Center for Paleoclimatology's International Tree-Ring Data Bank (ITRDB; available online at www.ngdc.noaa.gov/paleo/treering.html). In all but three cases (the Montana sites, where raw data were not available), raw ring-width measurements were used to generate tree-ring chronologies (ARSTAN; Cook 1985) to ensure that the same standardization process and conservative detrending methods were used for all chronologies. Also included were 11 newly generated chronologies from isolated ponderosa pine, Douglas-fir, and pinyon pine woodlands growing in the Great Plains in Nebraska, eastern and central Colorado, and northeastern New Mexico (Woodhouse and Brown 2001). Except for the three Montana chronologies, residual chronologies, from which low-order autocorrelation presumed to be biological in origin has been removed (Fritts 1976), were used for this study. Also shown are locations of gridpoint PDSI reconstructions used in Fig. 4 (circled X symbols).

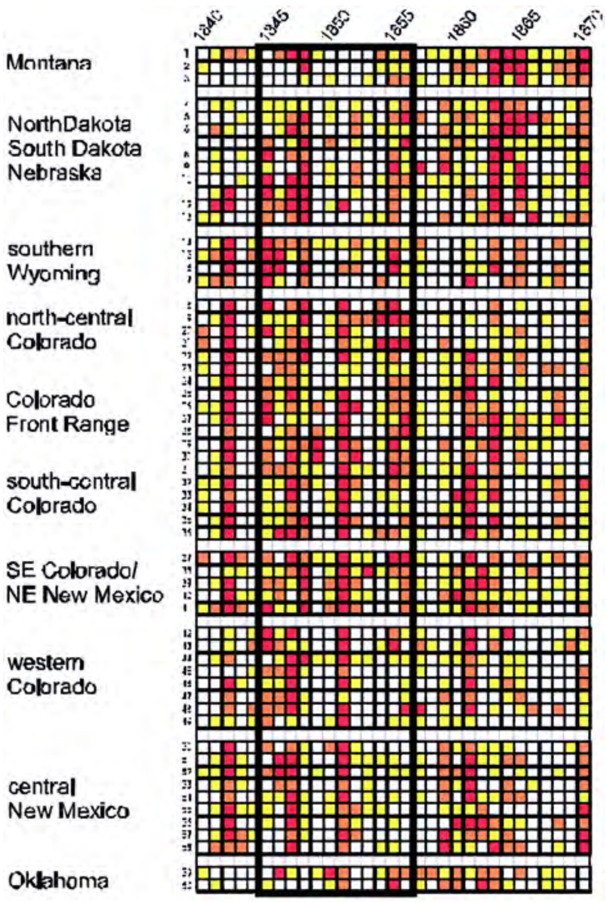

Fig. 3. Spatial distribution of low-ranking (narrow ring widths) years for 60 tree-ring chronologies, 1840–70. The chronologies were arranged by geographic region to illustrate patterns of low growth, a proxy for drought. The chronologies are grouped by region, from roughly north to south: the northern and central Great Plains, Colorado Front Range, eastern Colorado and northeastern New Mexico, western Colorado, central New Mexico, and Oklahoma. Annual ring-width indices for each of the 60 chronologies were ranked for the 285 yr 1680–1964. Rankings are shown for 1840–60 (major drought years outlined in black), the years that bracket the drought documented in the Colorado Front Range streamflow and eastern Colorado drought reconstructions, and for the 1860s central Great Plains drought, for comparison. The years in each chronology that fell within the lowest 50th, 25th, and 10th percentiles of growth were highlighted by red for a ranking below the 10th percentile, orange for the 10th–24th percentiles, yellow for the 25th–50th percentiles, and white for the above-median ranking.

turn to dry conditions in parts of Colorado. Drought prevailed again in eastern Colorado for three more years (1861–63), but dry conditions were scattered and only intermittent in the Front Range during these years.

The extent to which this mid-nineteenth-century drought spread eastward into the central Great Plains is unknown. Trees are scarce in this region, and tree-ring collections in central Kansas have yielded mostly young trees or samples that are difficult to date due to numerous interannual rings (Woodhouse and Brown 2001). Tree-ring chronologies from the southern and eastern flanks of the Great Plains do exist and have been used to reconstruct precipitation and drought (Blasing and Duvick 1984; Blasing et al. 1988; Stahle and Cleaveland 1988; Stahle et al. 1985; Cleaveland and Duvick 1992). Reconstructions for Texas, Oklahoma, and Arkansas show severe and prolonged drought peaking about 1860 (Blasing et al. 1988; Stahle and Cleaveland 1988; Stahle et al. 1985). Drought starts in the mid-1850s in this area, overlapping with the drought identified in eastern Colorado, but because of the difference in timing and location, this period of drought appears to be of a different nature than the 1845–56 Colorado drought. Reconstructions for Iowa and Illinois also show below-average moisture conditions in the mid-nineteenth century but conditions are only slightly below average during this period (Blasing and Duvick 1984; Cleaveland and Duvick 1992). To illustrate the differences in timing and/or magnitude of drought conditions suggested in the eastern and southern plains reconstructions described above, the gridpoint PDSI reconstructions from Cook et al. (2002) for the eastern and southern Great Plains, which use many of the same tree-ring data as well as data from Kansas, were examined (locations shown in Fig. 2, circled X symbols). A comparison of gridpoint reconstructions for the eastern (southwestern Iowa, northeast Kansas, the eastern Kansas and Oklahoma border, eastern Oklahoma, and northeastern Texas) and southern (central Oklahoma, northern Texas) plains and the two eastern Colorado reconstructions (eastern Colorado PDSI and Front Range streamflow; Woodhouse and Brown 2001; Woodhouse 2001) shows a difference in timing of drought conditions (Fig. 4). Although there is evidence of regional overlap, the Colorado drought is more strongly centered on the late 1840s, while the southern and eastern plains period of drought is centered on about 1860.

Although early instrumental records were kept at forts in Kansas and Nebraska, most records are few and fragmented until about 1858 (Mock 1991). Two longer records exist from Fort Leavenworth and Fort Scott in eastern Kansas and show several dry years in the 1840s and 1850s, but no period of sustained drought [the National Oceanic and Atmospheric

Administration's (NOAA's) Nineteenth-Century U.S. Climate Data Set Project; available online at www.ncdc.noaa.gov/onlinedata/forts/forts.html]. Other limited historical documents exist in the form of written accounts by early explorers traveling across the Great Plains in the eighteenth and nineteenth centuries. A review of reports documenting blowing sand from the Nebraska Sand Hills southward to northern Texas indicates multiple observations of eolian activity from about 1840 to 1865. It is, however, difficult to attribute activation of sand dunes to a specific drought year or set of years (Muhs and Holliday 1995). Along with the tree-ring data from the southern and central flanks of the Great Plains, these scant historical documents suggest an eastern limit of drought conditions during the period of sustained drought in eastern Colorado, 1845–56.

DROUGHT AND BISON. Bison (*Bison bison*) have been present in the Great Plains since at least the last glacial period, and evolved under a climate regime that included extensive periods of drought. Some research suggests a decline or even absence of bison remains in parts of the Great Plains during the markedly dry mid-Holocene, from about 8000 to 5000 yr B.P. (Dillehay 1974). (For the reader not familiar, B.P. refers to "before the present.") Other research clearly establishes that bison persisted during a part of the late Holocene that was far drier than the nineteenth century as demonstrated by numerous hoofprints in sand found in buried sand dune sediments in the west-central Great Plains (Muhs 2000; D. H. Muhs 2001, personal communication). Survival of the species dictated the development of behavioral adaptations to mitigate the impacts of drought, and likely included some degree of migration to areas less affected by drought (Flores 1991). A mass migration out of the Great Plains is not indicated during the dry mid-Holocene (Graham and Lundelius 1994), but we speculate that bison likely migrated to locally moister regions along riparian corridors.

In the last decade, the prevailing view that the abrupt near extinction of the bison in the nineteenth century was caused largely if not entirely by Euro-American market hunting after the Civil War has been challenged by some historians who have argued that the decline began in the 1840s and resulted from multiple interacting factors, including drought (Flores 1991; West 1995; Isenberg 2000). Given the survival of the species through periods of aridity lasting thousands of years, it is hard to believe a decadal-length drought in the nineteenth century had much of an impact on bison populations. However, the environment to which bison had long been adapted was systematically disrupted by human activities in the nineteenth century (Bamforth 1987).

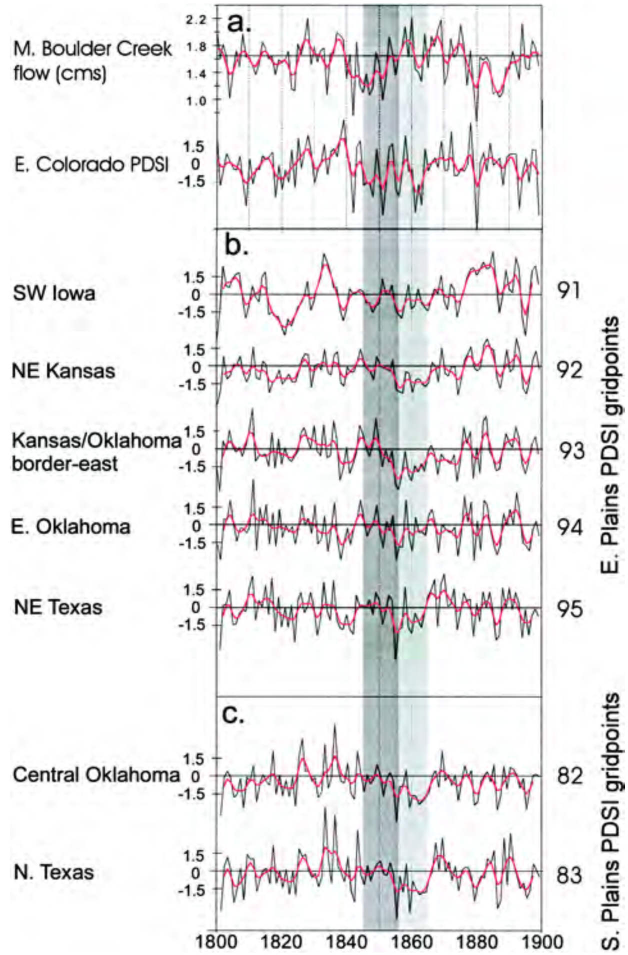

Fig. 4. Tree-ring reconstructions for drought (PDSI) and streamflow, 1800–99 with annual (black line) and smoothed (five-weight binomial filter, red line) values. Vertical shaded bars indicate eastern Colorado drought (1845–56, dark gray) and southern/eastern plains drought (1855–65, light gray line). (a) Colorado reconstructions (Woodhouse 2001; Woodhouse and Brown 2001), (b) eastern Great Plains gridpoint drought reconstructions from Cook et al. (2002), Nos. 91, 92, 93, 94, 95. (c) Southern Great Plains gridpoint drought reconstructions from Cook et al. (2002), Nos. 82, 83.

Flores (1991), using older tree-ring data from Nebraska, southern Wyoming, and the Colorado Front Range that indicated generally dry conditions in the southern and central Great Plains from 1846 to 1855 (Weakly 1943; Schulman 1956), proposed that drought was one of several causes of the collapse in bison populations across the Great Plains. This hypothesis was developed further by West (1995), also employing previous older dendroclimatological studies as well as historical accounts, who argued that generally reduced rainfall in the 1840s and 1850s, combined with increased grazing by both emigrants and Indians, severely impaired the forage resources of the uplands. Isenberg (2000) also attributed the bison population demise to a combination of cultural and environmental factors, including drought. The relatively lush and wooded river corridors through the western Great Plains had historically served as sheltered winter habitat and were likely year-round refugium for bison during drought as well (Flores 1991; West 1995). Beginning in the early 1840s, large caravans of both U.S. Army forces and Euro-American settlers, with thousands of horses and other livestock, traveled these corridors, severely reducing both forage and woodlands (West 1995). At the same time, the Native American populations of the western Great Plains, many of whom were relatively newcomers to this area, with their numerous horse herds, were increasing their usage of these same riparian corridors in response to the regional bison hide market created by newly established trading posts along the rivers (West 1995; Isenberg 2000). As a result, bison would have found much poorer conditions for subsistence during a period when these riparian areas would have been most critical. Studies during the 1930s and 1950s found that grass cover in the shortgrass uplands was dramatically reduced by drought (in one case from 90% to 20%) even in ungrazed areas (Malin 1947; Tomanek and Hulett 1970); during the drought in the mid-nineteenth century, conditions in the uplands may well have been worse. Poor upland range conditions and competition for riparian forage must have exacerbated the impacts of what was, in the context of the Holocene, a relatively minor drought. Thus, even though bison had persisted through much worse droughts in the mid- and late Holocene, human impacts on the Great Plains environment likely altered the bison's ability to cope with drought in the nineteenth century (West 1995).

The concurrent timing of the drought and the decline of the bison population lend further credence to drought as a possible pivotal factor. Reports of the reduction of bison numbers coincide, for the most part, with drought years documented by tree rings. The initial decline in the bison population was noted as early as 1844 (see footnote 40 of Flores 1991). This first report may have had less to do with drought than with a reportedly "epic" spring snowstorm in eastern Colorado in the spring of 1844 that apparently caused a local die-off of bison and other ungulates (Benedict 1999). However, by the late 1840s, anecdotal evidence from Kiowa painted robe calendars indicated few or no bison for the years 1849–52 (Flores 1991), and other historical accounts reflect a continued decline through the 1850s (West 1995).

Although the cause for the decline in bison in the nineteenth century remains a complex and much debated subject, the drought conditions reflected in the tree-ring records probably contributed to the demise of Great Plains bison. Our study, by more clearly describing the drought conditions at this time and by locating a core of drought along and east of the Front Range where bison populations apparently declined first (West 1995), reinforces the work of Flores (1991), West (1995), and Isenberg (2000) and adds even greater support to the idea that drought contributed to the bison population decline.

IMPORTANCE OF REGIONAL DROUGHT. This relatively small nineteenth-century drought would have had a very limited effect on the bison population if human activities had not been a factor. However, the severity and duration of this drought in eastern Colorado qualifies it as a major drought for this particular region. Although the size and length of this drought have been matched and exceeded by droughts in other areas, this drought is unique in terms of its impact on this region, having been unmatched here in at least the last three centuries. This drought, were it to occur today, would have considerable impacts now that the area includes a major, rapidly expanding metropolitan area as well as large-scale crop and livestock production. Large-scale droughts have obvious social, economic, and ecological impacts, but smaller-scale droughts may have significant impacts as well, which may be aggravated by location and timing.

An examination of small-scale droughts and their relationships to periods of more widespread drought is important for understanding why and where they may be likely to occur. While drought conditions were widespread during some of the years of this nineteenth-century drought, they appeared to contract into and persist in a core region in intervening years. Major droughts in the twentieth century, while more severe over larger areas, have displayed similar episodic fluctuations. The 1930s drought period had four distinct episodes of widespread dryness, and similar episodes occurred in the 1950s drought (Riebsame et al. 1991), with drought shrinking back to core regions between years of expansion (McGregor 1985). It is important to identify core areas within widespread droughts in order to assess possible significant regional impacts—and areas of drought susceptibility—that are not noted in larger-scale analyses. The core drought areas for both the mid-nineteenth-century drought described in this paper and the 1930s drought included southeastern Colorado.

In the western Great Plains, late spring and summer are the most important seasons with regard to drought, since this is when most of the annual precipitation occurs (Bryson 1966; Fritsch et al. 1986; Helfand and Schubert 1995; Mock 1996). Rainfall during this period can result from several different circulation mechanisms, including frontal systems drawing moisture from the Gulf of Mexico in the spring (Hirschboeck 1991); and in summer, the Great Plains nocturnal low-level jet (Tang and Reiter 1984; Helfand and Schubert 1995; Higgins et al. 1997); mesoscale convective complexes (Fritsch et al. 1986); and less commonly, synoptic-scale upper-level disturbances (Helfand and Schubert 1995; Mock 1996). Research suggests that conditions in both the Pacific and Atlantic Oceans can lead to drought in the Great Plains, directly or indirectly, by inducing perturbations in patterns of atmospheric circulation and the transport of moisture (Trenberth et al. 1988; Palmer and Branković 1989; Trenberth and Guillemot 1996; Ting and Wang 1997). Although studies have linked equatorial and northern Pacific conditions with spring and summer precipitation in the Great Plains, this relationship likely has more to do with Pacific sea surface temperature influences on circulation than direct transport of Pacific moisture (Ting and Wang 1997). On the other hand, drought in the Great Plains is strongly linked to the flow of moisture from the Gulf of Mexico in spring and summer, which is influenced by conditions in the Atlantic (Oglesby 1991; Helfand and Schubert 1995). Enfield et al. (2001) suggest that decadal-scale fluctuations in North Atlantic sea surface temperatures (SSTs) are related to drought in the central United States and also interact with ENSO variability. Thus, drought in the Great Plains may be caused by a number of different, but possibly interrelated factors over an area that included both the Atlantic and Pacific Oceans.

There is evidence to suggest that the drought conditions in eastern Colorado in the mid-nineteenth century were the result of several different overlapping droughts, each related to different circulation mechanisms. Recent work, using tree-ring and coral-proxy climate data, suggests that the severe drought centered around 1860 (roughly 1855–65) was linked to an unusually long, cold ENSO event, possibly enhanced by low-frequency variations in the extratropical Pacific (Cole et al. 2002). This event may have been a cause of the drought centered around 1860 seen in reconstructions for the southern Great Plains. However, the patterns of drought in the 1840s and early 1850s reconstructed from tree rings are less consistently representative of an ENSO cold event–drought pattern (Cole et al. 2002; also see PDSI reconstructions in Cook et al. 2002). This suggests that while ENSO may have been a factor in the latter years of the drought, other factors may have been responsible in earlier years of the drought. Unfortunately, no proxy records of Atlantic SSTs are yet available to test relationships with regional drought during the nineteenth century, but it is likely that a combination of circulation patterns, including those influenced by slowly varying conditions in both the Atlantic and Pacific Oceans, was responsible for mid-nineteenth-century drought conditions in the western Great Plains. Further investigation of the associated sea surface and atmospheric conditions for this time period through an analysis of independent proxy data, such as historical documents and other tree-ring data, could yield more information about possible causes of this mid-nineteenth-century drought.

CONCLUSIONS. This relatively small but persistent nineteenth-century drought in the west-central Great Plains likely influenced the cultural and ecological history of this region. If a drought of this duration and severity were to occur here today or in the future, impacts would be very different, but potentially as significant. The state of Colorado, and southeastern Colorado in particular, has experienced sustained, above-average precipitation for much of the last two decades (McKee et al. 1999), a period also characterized by rapid growth along the Front Range urban corridor. In the Colorado Front Range, water supply systems are commonly designed to handle the "drought of record," the most severe hydrologic event in the instrumental record (Howe et al. 1994). Although results of recent studies indicate that water managers from a variety of Front Range municipalities have considerable confidence in the reliability of their current water supplies (Howe and Smith 1993), how well would these cities and adjacent rural agricultural areas endure a decade-long drought?

The importance of identifying and understanding regional-scale drought should not be overlooked. Since instrumental records exist for only the past 100 years in many areas, the potential to study regional droughts based on instrumental data is limited. This study points to the continued need for filling in spatial gaps in high-resolution paleoclimatic data. The lack of a finescale network of paleoclimatic data can preclude detailed spatial analysis of past climate, but in this study, new data and a regionally focused analysis allow the identification of this regionally persistent drought. Global and large regional area reconstructions of past climate are very important for obtaining an understanding of patterns of past climate and for investigating possible large-scale controls. However, studies of past climate at smaller regional scales are of utmost importance especially in areas such as the western Great Plains, where the cultural and ecological history are entangled and disputed issues exist, and the Colorado Front Range where an event the magnitude of the mid-nineteenth-century drought would have major societal, economic, and ecological impacts were it to occur today.

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REFERENCES

Bamforth, D. B., 1987: Historical documents and bison ecology on the Great Plains. *Plains Anthropol.,* **32,** 1–16.

Benedict, J. B., 1999: Effects of changing climate on game-animal and human use of the Colorado high country (U.S.A.) since 1000 BC. *Arct. Antarct. Alp. Res.,* **31,** 1–15.

Blasing, T. J., and D. N. Duvick, 1984: Reconstruction of precipitation history in North American corn belt using tree rings. *Nature,* **307,** 143–145.

——, D. W. Stahle, and D. N. Duvick, 1988: Tree ring-based reconstruction of annual precipitation in the south-central United States from 1750 to 1980. *Water Resour. Res.,* **24,** 163–171.

Bryson, R. A., 1966: Air masses, streamlines, and the boreal forest. *Geogr. Bull. (Can.),* **8,** 228–269.

Cleaveland, M. K., and D. N. Duvick, 1992: Iowa climate reconstructed from tree rings, 1640–1982. *Water Resour. Res.,* **28,** 2607–2615.

Cole, J. E., J. T. Overpeck, and E. R. Cook, 2002: Multiyear La Nina events and persistent drought in the contiguous United States. *Geophys. Res. Lett.,* **29** (13), 1647, doi: 10.1029/2001GL13561.

Cook, E. R., 1985: A time series analysis approach to tree-ring standardization. Ph.D. dissertation, The University of Arizona, 171 pp.

——, D. M. Meko, D. W. Stahle, and M. K. Cleaveland, 1996: Tree-ring reconstructions of past drought across the coterminous United States: Tests of a regression method and calibration/verification results. *Tree rings, Environment, and Humanity,* J. S. Dean, D. M. Meko, and T. W. Swetnam, Eds., Radiocarbon, 155–169.

——, ——, and C. W. Stockton, 1997: A new assessment of possible solar and lunar forcing of the bidecadal drought rhythm in the western United States. *J. Climate,* **10,** 1343–1356.

——, ——, D. W. Stahle, and M. K. Cleaveland, 1999: Drought reconstructions for the continental United States. *J. Climate,* **12,** 1145–1162.

——, ——, ——, and ——, cited 2002: Reconstruction of past drought across the counterminous United States from a network of climatically sensitive tree-ring data. [Available online at http://www.ngdc.noaa.gov/paleo/pdsiyear.html.]

Dillehay, T. D., 1974: Late Quaternary bison population changes on the southern Plains. *Plains Anthropol.,* **19,** 180–196.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.,* **28,** 2077-2080.

Flores, D., 1991: Bison ecology and bison diplomacy: The southern Plains from 1800 to 1850. *J. Amer. Hist.,* **78,** 465–485.

Fritsch, J. M., R. J. Kane, and C. R. Chelius, 1986: The contribution of mesoscale convective weather systems to the warm season precipitation in the United States. *J. Climate Appl. Meteor.,* **25,** 1333–1345.

Fritts, H. C., 1965: Tree-ring evidences for climatic changes in western North America. *Mon. Wea. Rev.,* **93,** 421–443.

——, 1976: *Tree Rings and Climate.* Academic Press, 567 pp.

——, 1983: Tree-ring dating and reconstructed variations in central Plains climate. *Trans. Nebraska Acad. Sci.,* **11,** 37–41.

Graham, R. W., and E. L. Lundelius Jr., 1994: Faunmap: A database documenting late quaternary distributions of mammal species in the United States. Illinois State Museum Scientific Papers, Vol. XXV, No. 2, Illinois State Museum, Springfield, IL, 403 pp.

Helfand, H. M., and S. D. Schubert, 1995: Climatology of the simulated Great Plains low-level jet and its contribution to the moisture budget of the United States. *J. Climate,* **8,** 784–806.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak, and K. C. Mo, 1997: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. *J. Climate,* **10,** 481–507.

Hirschboeck, K. K., 1991: Climate and floods. National Water Summary, 1988–89—Floods and Droughts: Hydrologic Perspectives on Water Issues. USGS Water-Supply Paper 2375, 591 pp. [Available from USGS Information Services, Box 25286, Denver Federal Center, Denver, CO 80225.]

Howe, C. W., and M. G. Smith, 1993: Incorporating public preference in planning urban water supply reliability. *Water Resour. Res.,* **29,** 3363–3369.

——, ——, L. Bennett, C. M. Brendecke, J. E. Flack, R. M. Hamm, R. Mann, L. Rozaklis, and K. Wunderlich 1994: The value of water supply reliability in urban water systems. *J. Environ. Econ. Manage.,* **26,** 19–30.

Isenberg, A. C., 2000: *The Destruction of the Bison.* Cambridge University Press, 206 pp.

Karl, T. R., and A. J. Koscielny, 1982: Drought in the United States: 1895–1981. *J. Climatol.,* **2,** 313–329.

Malin, J. C., 1947: *The Grassland of North America.* Edward Brothers, 398 pp.

McGregor, K. M., 1985: Drought during the 1930s and 1950s in the central United States. *Phys. Geogr.,* **6,** 188–301.

McKee, T. B., N. J. Doesken, J. Kleist, and C. J. Shrier, 1999: A history of drought in Colorado: Lessons learned and what lies ahead. *Water in the Balance,* No. 9, Colorado Water Resources Research Institute, 20 pp.

Meko, D. M., 1992: Dendroclimatic evidence from the Great Plains of the United States. *Climate Since A.D. 1500,* R. S. Bradley and P. D. Jones, Eds., Routledge, 312–330.

Mock, C. J., 1991: Drought and precipitation fluctuations in the Great Plains during the late nineteenth century. *Great Plains Res.,* **1,** 26–56.

——, 1996: Climatic controls and spatial variations of precipitation in the western United States. *J. Climate,* **9,** 1111–1125.

Muhs, D. R., 2000: Evidence of middle and late Holocene drought from eolian records of midcontinental North America. *Abstracts, 16th Biennial Meeting,* Fayetteville, AR, American Quaternary Association, 29–33.

——, and V. T. Holliday, 1995: Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers. *Quat. Res.,* **43,** 198–208.

Oglesby, R. J., 1991: Springtime soil moisture, natural climatic variability, and North American drought as simulated by the NCAR Community Climate Model 1. *J. Climate,* **4,** 890–897.

Palmer, T. N., and Č. Branković, 1989: The 1988 U.S. drought linked to anomalous sea surface temperature. *Nature,* **338,** 54–57.

Palmer, W. C., 1965: Meteorological drought. U.S. Weather Bureau Research Paper 45, U.S. Department of Commerce, 58 pp.

Riebsame, W. E., S. A. Changnon, and T. R. Karl, 1991: *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987–89 Drought.* Westview Press, 174 pp.

Robbins, J., 1999: Historians revisit slaughter on the Plains. *New York Times,* 16 November.

Schulman, E., 1956: *Dendroclimatic Change in Semiarid America.* University of Arizona Press, 142 pp.

Stahle, D. W., and M. K. Cleaveland, 1988: Texas drought history reconstructed and analyzed from 1698 to 1980. *J. Climate,* **1,** 59–74.

——, ——, and J. G. Hehr, 1985: A 450-year drought reconstruction for Arkansas, United States. *Nature,* **316,** 530–532.

Stockton, C. W., and D. M. Meko, 1983: Drought recurrence in the Great Plains as reconstructed from long-term tree-ring records. *J. Climate Appl. Meteor.,* **22,** 17–29.

Tang, M., and E. R. Reiter, 1984: Plateau monsoons of the Northern Hemisphere: A comparison between North America and Tibet. *Mon. Wea. Rev.,* **112,** 617–637.

Ting, M., and H. Wang, 1997: Summertime U.S. precipitation variability and its relation to Pacific sea surface temperature. *J. Climate,* **10,** 1853–1873.

Tomanek, G. W., and G. K. Hulett, 1970: Effects of historical droughts on grassland vegetation in the central Great Plains. *Pleistocene and Recent Environments of the Central Great Plains,* W. J. Dort Jr. and J. K. Jones Jr., Eds., University of Kansas Press, 203–210.

Trenberth, K. E., and C. J. Guillemot, 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. *J. Climate,* **9,** 1288–1298.

——, G. W. Branstrator, and P. A. Arkin, 1988: Origins of the 1988 North American drought. *Science,* **242,** 1640–1645.

Weakly, H. E., 1943: A tree-ring record of precipitation in western Nebraska. *J. For.,* **41,** 816–819.

West, E., 1995: *The Way to the West: Essays on the Central Plains.* University of New Mexico Press, 244 pp.

Woodhouse, C. A., 2001: Tree-ring reconstruction of mean annual streamflow for Middle Boulder Creek, Colorado, USA. *J. Amer. Water Res. Assoc.,* **37,** 561–570.

——, and J. T. Overpeck, 1998: 2000 years of drought variability in the central United States. *Bull. Amer. Meteor. Soc.,* **79,** 2693–2714.

——, and P. M. Brown, 2001: Tree-ring evidence for Great Plains drought. *Tree-Ring Res.,* **59,** 89–103.