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Quantification of Climate Conditions Important to the Tall Grass Prairie

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ABSTRACT

The geologic history of the tall grass prairie in central North America reveals the prairie began developing 10,000 years ago after the Pleistocene ice sheets had retreated into Canada. The long-lived triangular shaped prairie survived several climatic shifts during the Holocene. Scientists have studied the anomaly—grasses where many climate conditions indicate forests should have been growing—by offering a myriad of potential climate, physiographic, and human factors. By the 1960s scientists recognized that fire was the key to the prairie's presence—fires destroyed forests but grasses survived and were generally enhanced by prairie fires. Scientists have since believed that lightning, in addition to fires set by Native Americans, were the reasons for the region's high frequency of prairie fires. Long records of various climate conditions collected since the 1890s now allow a quantitative comparison of the prairie versus non-prairie climate conditions. Assessment of drought conditions during the 20th Century shows that the prairie triangle experienced 50% to 200% more severe drought years than did the forested areas north and south of the prairie, an important factor behind the prairie's presence. Cold season precipitation, averaging <34 cm, in the prairie was too low to sustain the deciduous forests that grew south and east of prairie, and resulted in a dry season necessary for frequent prairie fires. The rougher topography and numerous streams to the prairie's south also served as firebreaks to contain fires, whereas the flat lands of the prairie with few major rivers had fewer natural firebreaks. West of the tall grass prairie was a short grass prairie, the climax vegetation in the more arid High Plains. Large differences in lightning activity exist along the prairie's northern boundary during the prairie's fire season (October-March), suggesting that the much lower storm incidences to the north help explain the presence of forests in that area. Long climatic records, which were not available for use in earlier studies, have allowed quantification of the climate factors that helped shape the Midwest's tall grass prairie.

INTRODUCTION

The North American tall grass prairie was in a triangular-shaped area and its approximate corner points were near where Tulsa, Fargo, and Indianapolis now exist (Fig. 1). Its presence has represented a scientific challenge to identify and quantify the climatic and other physical variables that established and maintained it as a grassland (Risser et al., 1981). Many considered it a unique grassland unmatched elsewhere on the globe. Before settlement by Europeans, this huge area labeled as the "inland sea" by early explorers was covered by tall grasses ranging from 0.5 to 2 meters tall with tree stands mainly along the region's major rivers,

Two climate-driven events in the 20th Century have increased research relevant to the prairie and its climate. One was the severe droughts of the 1930s, and the other has been scientific concern over the potential impacts of future changes in climate. Climate data of 100 years in length from the 20th century have become available and were assessed to quantify the region's climate conditions believed to have helped develop and sustain the prairie.

GEOLOGIC-CLIMATIC HISTORY

To understand the formation of the tall grass prairie., one must go back into the region's geologic past. During the Pleistocene Epoch, which lasted approximately 2 million years, there were several major glacial advances and retreats into the region, labeled as glacial stages. Each stage brought continental-scale ice sheets that covered various parts of prairie area, and most of the tall grass prairie was covered at least once and often twice by the massive ice sheets. Each glacial advance scoured the surface, and brought and deposited vast quantities of sands, soils, and rocks, labeled as glacial drift, ultimately creating a rather flat surface composed of glacial outwash materials over most of the area where the prairie later developed. To the south of these giant ice sheets, spruce-dominated boreal forests grew (Watts, 1983). During the long interglacial periods, the boreal forests developed northward into the area where prairie ultimately developed. When the next glacial advance came, these advancing forests were eliminated.

The Laurentide ice sheet of the last glacial stage began to retreat 14,000 years B.P. and was largely gone from the prairie area about 11,500 years ago (Porter, 1983). Since then geologists consider that we have been in an interglacial period named the Holocene. The soil over most of the future prairie area developed from the major deposits of loess, the fine sediments blown by dust storms resulting from the strong westerly winds of the post-glacial climate. The soils of the prairie are primarily Mollisols, types found in mid- to tall-grasslands. These are now the rich soils of the Corn Belt.

In the centuries after the glaciers retreated, the region's climate became more similar to that of today but with continuing variations, predominantly westerly winds, and interactions of Gulf moist air creating precipitation (Barry, 1983). The spruce-dominated boreal forests had moved northward as the ice sheets melted, not simply because the climate of the prairie area had changed from optimal for them, but because other forest varieties now had a competitive edge (Bryson, 1966). Deciduous forests then developed in the tall grass prairie about 10,500 years B.P. (Watts, 1983). As the climate continued to warm and become drier, grasslands replaced the forests across the prairie area from 10,000 years B.P. (western sections), to 8,000 years ago (in the eastern parts of the ultimate tall grass prairie), becoming the primary vegetation (King, 1981). To the north, mixed coniferous and deciduous forests developed, and to the south, deciduous forests remained (Wright, 1976). The climate to the west of the tall grass prairie was much drier and there a short grass prairie evolved. The eastern two-thirds of the tall grass prairie (northeastern Missouri, eastern Iowa, southern Wisconsin, Illinois, and Indiana) was a savanna, a grassland with scattered trees plus groves of trees along the main river courses and in some uplands (King, 1981).

There have been sizable climate fluctuations in the tall grass prairie during the 11,000-year long Holocene. Seven major shifts in the area's climate conditions occurred during the Holocene, and each was relatively abrupt (Bryson et al., 1970). A shift to cooler and wetter conditions began about 4,000 B.P., and the last 3,000 years of the Holocene have been relatively cool and similar to the current climate (Guetter and Kutzbach,1990). Through all of these shifts, the tall grass prairie survived.

However, the boundaries of the prairie were not fixed and shifted over time as a result of the multi-century fluctuations in the climate conditions optimum for grasses and forests. For example, Albertson and Weaver (1944) show that short grasses moved several kilometers east into the tall grass region as a result of devastating droughts of the 1931-1940 period. Bryson (1974) found that a major dry period that began 3,800 B.P. and lasted 200 years caused much of the tall grasses in the western prairie to be replaced by short grasses. But, after a moister regime returned, the tall grasses again took over. During the peak of the warmer and drier period of the Holocene, the prairie also expanded eastward into parts of Ohio and western Pennsylvania. Trees began to invade the southern boundaries of the prairie during the Little Ice Age (Grimm et al., 2001). Although the forested boundaries have fluctuated over time, most of the tall grass prairie area shown on Figure 1 persisted as a grassland over the past 8,000 years (Risser et al., 1981). A recent analysis concludes that the wetter and cooler climates of the past 4,000 years established the region's modern vegetative pattern (Grimm et al., 2001).

CAUSES FOR THE TALL GRASS PRAIRIE

Throughout most of the 20th Century numerous climatologists, geographers, geologists, and ecologists have assessed why tall grasses prevailed in a region with humid climate conditions also found elsewhere to be quite suitable for forests. The factors seen as important for the prairie's presence included the region's topography, soils, climate, and human presence.

Topography has long been seen as a factor behind the vegetative differences. In particular, the areas south of the prairie, much of which was unglaciated during the Pleistocene, was a region with more erosion, and with ridges and hills, steep slopes, and a well-developed drainage system with numerous rivers and streams. The forested areas to the north of the prairie also had an important physiographic difference–the area included numerous small lakes and bogs. The tall grass prairie was exceptionally flat with poor drainage. Thus, topography is a key factor related to the placement of the north and south boundaries of the prairie, but the topography to the west was not strikingly different and has not been seen as a cause of that boundary.

The various factors underlying the presence of the tall grass prairie were being assessed in an era when scientists had finally concluded that soil types were largely caused by climate with some control from the local topography (Risser et al., 1981). This included the direct physical effects of climate conditions on the parent material (heavy rains, freeze-thaw cycles, etc.), and the indirect effects of climate that determine the vegetative cover.

Vegetation, in turn, helps create the soil beneath it. Thus, one postulated factor for explaining the prairie, the soils, was eliminated as a prime factor. Soils were largely a result, not a cause of the prairie.

A variety of climatic differences in temperatures and precipitation existed along the prairie's three boundaries—the south, north, and west. Numerous climatological conditions have been postulated as reasons for the tall grass prairie. It was relatively easy to explain and understand the western boundary where the tall grass prairie shifted to a mixture of short and long grasses. The demarcation was a direct result of the drier climate to the west. As early as 1938 the close spatial relationship between the short grass prairie's eastern boundary and the 20-inch (51 cm) isohyet of average annual precipitation (Fig. 2) was detected (Mattice, 1938). Others explained that the western boundary was a result of the fact that the short grass area to the west had more runs of days with exceptionally high temperatures and more intense droughts, all of which created the drier, semi-arid climate (Thornthwaite, 1941; Borchert, 1950).

An important scientific breakthrough occurred after upper air measurements had been started by the U.S. Weather Bureau in the 1930s. By the 1950s the concept that air mass patterns could help explain vegetation patterns appeared (Brunschweiler, 1952). Mean monthly streamline (air flow) patterns for the cold season (October-March) showed a separation between the prevailing maritime tropical (mT) air mass and the mild Pacific (cP) air mass, and their average boundary was a curved line closely matching the southern boundary of the tall grass prairie (Bryson, 1966). The streamline patterns for the warm season (April-September) established a boundary between the dry cP air mass over the prairie area and the prevailing Arctic air mass to the north, and this border was close to the northern boundary of the tall grass prairie. On average, the prairie area was dominated from November through March by the modified Pacific air (that had become dry after passage over the Rockies), and from June through September, mT air prevailed in the southern portions of the prairie and cP air in the north, a condition conducive to convective storms and rainfall (Bryson et al., 1970). These findings helped establish the large-scale climatic controls that apparently helped shape the prairie. The presence of the dry westerlies was a key climate control for the prairie region, but what mattered to the vegetation was the resulting mix of climate conditions at the surface. Now, at the start of the 21st Century we have 100+ years of quality climatic data to examine the important climatological conditions at the surface, and to quantify their effects on establishing the boundaries of the tall grass prairie.

IMPORTANT SURFACE CLIMATE CONDITIONS

Numerous studies since the 1930s concluded that a key factor separating the tall grass prairie from the forested areas north and south was drought, a result expected from the prevailing dry westerlies (Bryson et al., 1970). Most earlier studies had used short periods of data, 10 to 30 years, to try to assess drought, and generally inadequately defined drought as just a precipitation deficiency. Studies had shown that during the warmer and drier eras of the Holocene the prairies had moved eastward into parts of Ohio, Pennsylvania, and West Virginia, and then retreated westward as more humid conditions returned (Bryson, 1974; Grimm et al., 2001)). By the 1970s a means for quantifying droughts and involving soil moisture conditions, had been developed. These were the Palmer Drought

Severity Indices, and Figure 3 shows the drought frequencies based on the indices for each climate district. Shown are the frequency of droughts classed as severe or extreme, expressed as a percent of years during the 1895-1995 period. Comparison of the area with droughts during 10% to 15% of the years (labeled area 3 in Fig. 3) with the boundaries of the prairie shows close agreement. The various climate districts within the tall grass prairie had experienced severe to extreme droughts between 10% and 15% of the years, whereas the forested areas north and south of the prairie had such droughts in only 5% to 10% of the years. These results reveal drought occurred 50% to 200% more often in the prairie, illustrating the importance of drought in establishing the regional boundaries between prairie and forests.

Another climate condition that had been identified as important, when better understanding of the relationship between climate conditions and tree varieties developed, was the critical importance of year-round humid soil conditions for many deciduous tree varieties. The oak-hickory forest to the south of the prairie, an area with higher mean annual temperatures than the prairie, has a precipitation-evapotranspiration ratio of 0.5 to 1.0 (Holdridge, 1964). Such a warm and moist deciduous forest requires an annual average precipitation of 85 cm to 200 cm, and furthermore the precipitation must be well distributed throughout the year (Malin 1947). The 85- and 100-cm isohyetal lines of average annual precipitation for the 20^{th} Century (Fig. 4) are close and parallel to the southern boundary of the tall grass prairie. Figure 4 also shows that 40% or more of the annual precipitation south of the prairie occurs in the colder half-year (October-March), and hence the southern forested area has no dry season. Most cold season precipitation values in the tall grass prairie are 25% to 35% of the total (Fig. 4), forming the relatively dry season that also has been recognized as a key feature of prairies (Malin, 1947). The wetter colder half year in the southern and eastern forests also acted to reduce the potential for fires, and this also limited the spread east and south of the prairie (Komarek, 1964). The heavier cold season precipitation of >34 cm (85 cm x 40%) helps define the boundary between the prairie and the southern forested area. The drier cold season in the forests north of the prairie is not tree limiting since the temperatures and P-E ratios are much lower and not limiting to several tree varieties in the area (Grimm, 1983).

The year-round humid conditions to the south of the prairie (Fig. 4), plus the rougher terrain with many more rivers and streams serving as firebreaks, forestalled major fires and produced a situation conducive to forests and not grasslands. The year-round heavy monthly precipitation and higher moisture supply did not allow sufficient dryness for lightning-induced fires to be ignited, and sustained the moisture needs of the major tree varieties. Figure 3 also shows that fewer severe droughts occurred south of the prairie.

None of the temperature or precipitation reasons offered for the tall grass prairie completely explained the presence of grasses where forests of certain varieties would also normally grow. Trees did grow in isolated stands and also along the banks of some rivers in Illinois and other parts of the eastern tall grass prairie, but much of the area was in grass. Much of the eastern portion of the prairie was a savanna vegetation dominated by the tall grasses. Field studies in Illinois found 70% of the prairie area had tall grasses and 30% trees (King and Johnson, 1977).

Sauer (1950) was one of the first investigators to identify fire as a key to the prairie's existence. His studies of grasslands around the world identified three key conditions for grasslands: a) a dry season, b) a land surface that is flat to rolling, and c) fire. Forests are destroyed by fire and only slowly re-establish themselves after being burned, whereas grasslands are enhanced by fires (Daubenmire, 1968; Anderson, 1970). The grasses had buds and seeds that lay just below the soil surface where fire temperatures were low. After the fires occurred in the fall, winter, or early spring, consuming the above-surface dry material, the grasses re-developed normal shoots in a short period of time (Axelrod, 1985). Thus, prairie fires were a key to the presence of the prairie grasses. Daubenmire (1978) labeled the tall grass prairie as a "fire-induced ecotone." The prairie-forest boundaries, or ecotones, were largely stabilized by natural firebreaks (Grimm, 1983, 1984). Several studies have shown that the cessation of prairie fires after the area's European settlement in the 19th Century has resulted in forest invasions along the borders of the grasslands (Ahlgren, 1960; Briggs and Hurlbert,1976; Daubenmire, 1968). Today it is well recognized that fire is an important instrument in managing and enriching prairie ecosystems (Larrabee and Altman, 2001)

The tall grass prairie was extremely flat with few natural firebreaks, thus allowing prairie fires to move unabated (Jackson, 1965). Movement of prairie fires has been measured to be as high as 15 to 20 km/hr (Risser et al., 1981), and they often moved west to east with prevailing winds, allowing tree stands to develop on the lee (east) side of the region's rivers (Daubenmire, 1978). The effect of the Mississippi River and the topography of its river valley that served as a firebreak is revealed by the shape of the grasslands shown in Figure 1 (Brigham and Patterson, 1996). The prairie was replaced by trees along the river banks but the prairie existed a few kilometers away from both sides of the river.

The causes for the prairie fires have been seen as the actions of Native Americans and lightning, and debate has occurred over their relative importance. King (1981), in an assessment of the vegetative history of the tall grass prairie, noted the importance of fires to its development and stated, "The role and importance of both natural (lightning) and anthropogenic fires in the history of the Prairie Peninsula will undoubtedly be debated further."

Early settlers had recorded that the fires had been a result of actions by Native Americans (Anderson, 1970; Donovan, 1992). Native Americans first appeared in the tall grass prairie after it had formed, and as hunters, they followed on foot the herds of bison for food (Larrabee and Altman 2001). The herds preferred to feed on the newly emerging shoots of grass that appeared after fires burned the overlying dead matter, and by observation, the Native Americans saw this fresh grass feeding choice, and in turn used fire as a way to establish hunting grounds in the following spring season.

A forest expert in the 1960s noted that many prairie fires had also been set by lightning (Komarek, 1964). Komarek made an extensive review of past research on lightning and its impacts on crops and trees, and noted that "little if any comment has been made about natural fires set in the prairies by lightning." Large burns induced by lightning were maintaining the prairie for many years before Native Americans occupied the tall grass prairie (Larrabee and Altman, 2001). Examination of hundreds of accounts of early settlers in the tall grass prairie during the 1535-1890 period revealed reports of 403 prairie fires with 183 attributed to native Americans, 111 to settlers, and 212 to lightning (Moore, 2001). These notes had numerous reports of tree fires ignited by lightning and these also likely led to grass fires. The savanna portion of the prairie was conducive to the tree-related initiation of prairie fires. Jackson (1965), who had studied the ledgers of those who herded cattle across the prairies, noted that many contained reports about the incidence of lightning-induced prairie fires. A leading ecologist who made an extensive assessment of fires in grasslands around the world pointed to the importance of lightning as the key factor (Daubenmire, 1968). An extensive study of the tall grass prairie in the late 1970s led a group of ecologists to conclude that lightning-created fires, as well as those caused by native Americans, had frequently swept over the prairie in the fall and early spring when the extensive dry grass matter created during the cold dry season was very flammable (Risser et al., 1981).

Newly available nationwide thunderstorm data for the entire 20th century (Changnon, 2001a) permitted a study of thunderstorm activity in the region to gain a perspective on their regional potential for fires. The prairie is located in one of the three prime areas of thunderstorm activity in the United States, averaging 60 to 80 thunderstorm events a year, with more than 10,000 minutes per year with storm activity at any point in the region (Changnon, 2001b). Only the Gulf Coast and Florida average more storms. Thunderstorm incidences during the October – March period, defined as the prairie fire season (Jackson, 1965), were determined. The average fire season values of thunderstorms were found to differ greatly along the northern boundary of the tall grass prairie. The pattern of fire season storm frequencies (Fig. 5) shows that most weather stations in the northern forested area (northern Minnesota, northern Wisconsin, and all of Michigan) average between 1 and 2 days with thunderstorms from October through March. Stations to the immediate south and located in the prairie, average 3 to 6 storm days during the fire-prone season. Thus, storms in the prairie area are three to six times more frequent than those north of the prairie boundary. Analysis of cloud-to-ground lightning flashes during 1989-1996 showed a dramatic decrease northward. The annual average is 13 to 15 strokes per 2 km^2 in the Illinois-Iowa portions of the prairie, but less than 1 stroke per 2 km^2 in the northern forested area (Huffier and Orville, 1999).

Lightning-caused fires, along with those caused by the actions of Native Americans, were major reasons for the tall grass prairie—the fires destroyed most forests but sustained the grasses. The sharp regional difference in storm frequencies during the fire season (Fig. 5) appears to have been another reason for the boundary between the prairie and the northern forests, and the northern terrain has more natural firebreaks to restrain fires when set. The area to the north of the prairie also had much less frequent intense droughts, as shown in Fig. 3, which further restrained the incidence of fires.

The western boundary separating the tall and short grass prairies was primarily related to the greater frequency of severe droughts to the west (Fig. 3), to lower annual precipitation (Fig. 2), and to higher evapotranspiration. The short grass prairie to the west of the tall grass prairie also had fewer fire-season thunderstorms (Fig. 5), but did experience major prairie fires (Jackson, 1965).

SUMMARY

The climate conditions important to the presence of the tall grass prairie and its ecotones, or boundaries, have been quantified using 20th century climate data. This assessment is meaningful because the climate of the 20th Century was representative of that in major portions of the Holocene, as Guetter and Kutzback (1990) have shown. Wright (1968) and Grimm et al. (2001) concluded that the present climate conditions in the tall grass prairie area have existed since 4,000 years B.P.

The tall grass prairie was present for 8,000 (eastern sections) to 10,000 (western sections) years ago in central North America because of several factors. These included the region's topography (flat with poor drainage), regional climate conditions featuring frequent droughts and a dry cold season, and fires caused by Native Americans and lightning. The post Ice Age prevailing patterns of atmospheric circulation over the region created a climate that was conducive to either forests or grasses, but the grasses prevailed mainly due to the region's susceptibility to fire. The vegetative boundaries of the triangular-shaped region were determined by differences in drought frequency and the physical factors related to fires and their control, including regional differences in moisture, thunderstorms, and topography.

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Figure 1. The tall grass prairie and other major prairie areas in the United States prior to European settlement (from Risser et al., 1981).

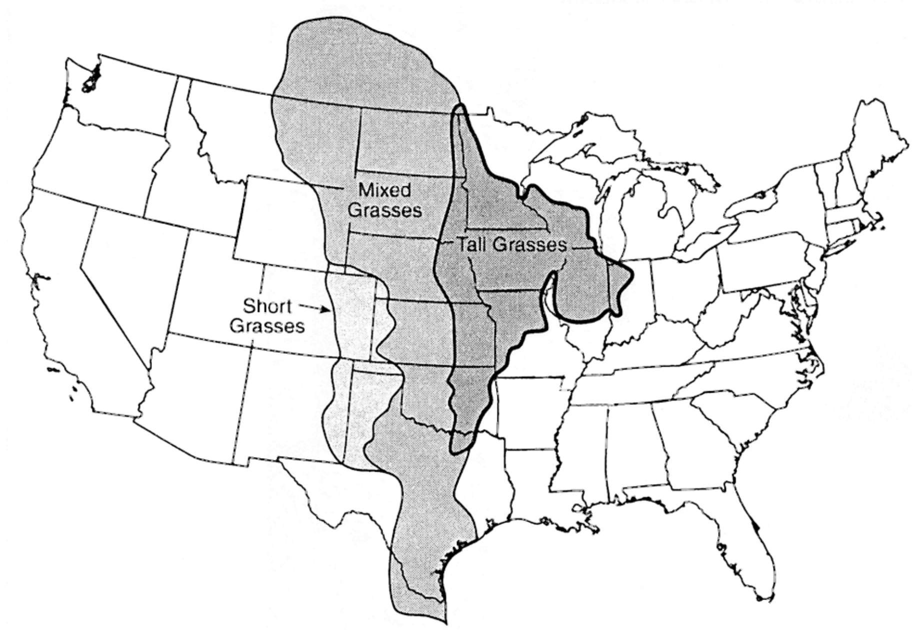

Figure 2. Lines marking major regional differences in climate and grasslands, as noted in 1938 (from Mattice, 1938).

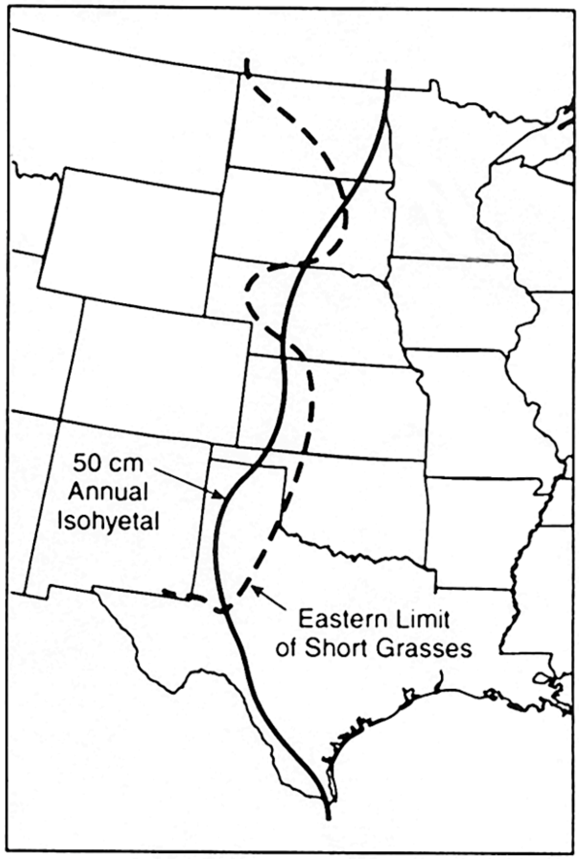

Figure 3. Pattern based on the percent of years that experienced severe or extreme drought, based on the Palmer Drought Severity Index values for climate districts during 1895-1995.

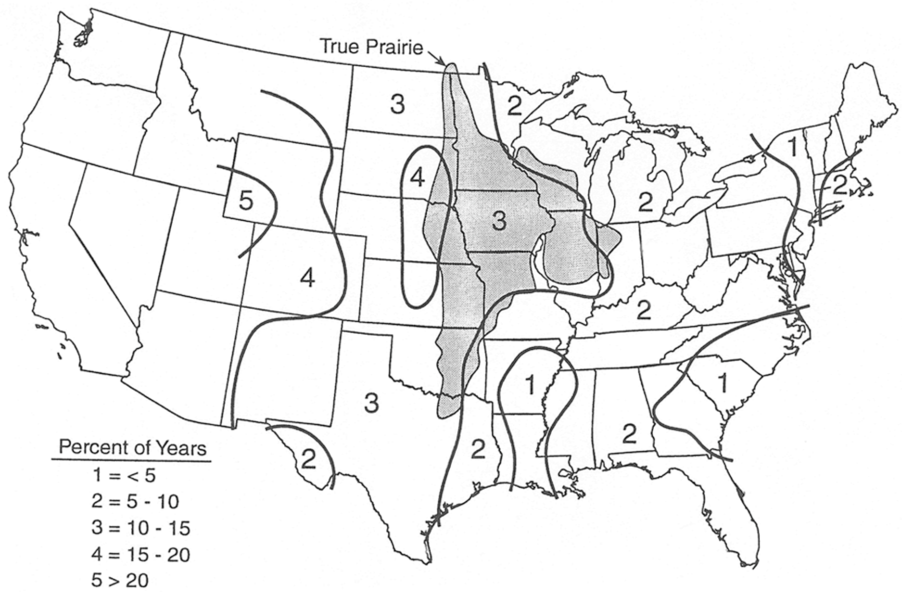

Figure 4. The average cold season (October-March) precipitation expressed as a percent of the annual total, and the isohyetals of annual average precipitation of 85 and 100 centimeters, based on data for 1901-1997.

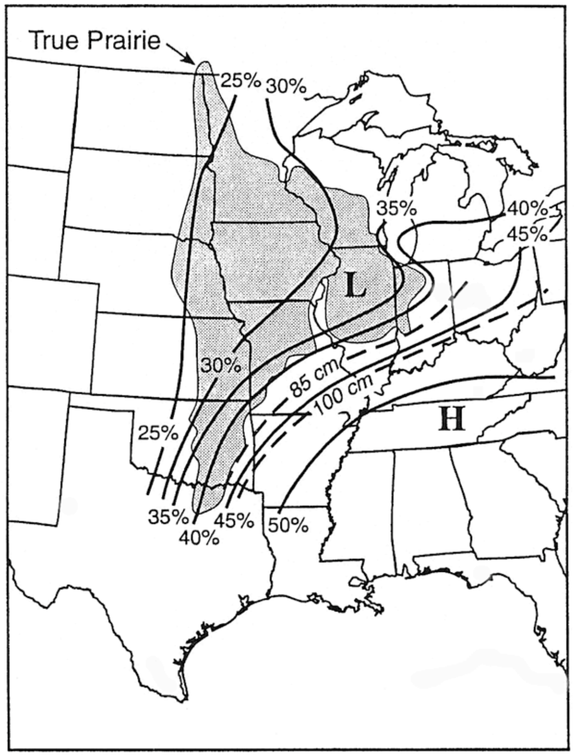

Figure 5. Pattern based on the average number of days with thunderstorms during the prairie fire season, October-March, based on data for 1901-1995.