Plant Water Stress Frequency and Periodicity in Western North Dakota

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Water stress develops in plants when the rate of water loss from transpiration exceeds the rate of water absorption by the roots. The excessive loss of plant water causes cells to lose turgor and, consequently, wilting of plant structures. Water stress reduces plant growth and development during growing season months with water deficiency which results when precipitation amounts are lower than the evapotranspiration rates. Conditions that create water deficiencies are variable with monthly changes in temperature and precipitation. Soil water losses increase with increases in evapotranspiration demand. Evaporation rates increase as temperature increases. For each increase of 1° C in mean monthly temperature, an increase of 2 mm of monthly precipitation are required to prevent water deficiency and plant water stress. Plants in water stress have limited growth and herbage biomass accumulation. Water stress can vary in degree from a small decrease in water potential, as in midday wilting on warm, clear days, to the lethal limit of desiccation. Early stages of water stress slow shoot and leaf growth. Leaves show signs of wilting, folding, and discoloration. Tillering and new shoot development decrease. Root production may increase. Senescence of older leaves accelerates. Rates of cell wall formation, cell division, and protein synthesis decrease. As water stress increases, enzyme activity declines and the formation of necessary compounds slows or ceases. The stomata begin to close; this reaction results in decreased rates of transpiration and photosynthesis. Rates of respiration and translocation decrease substantially with increases in water stress. When water stress becomes severe, most functions nearly or completely cease and serious damage occurs. Leaf and root mortality induced by water stress progresses from the tips to the crown. The rate of leaf and root mortality increases with increasing stress. Water stress can increase to a point that is lethal, resulting in damage from which the plant cannot recover. Plant death occurs when meristems become so dehydrated that cells cannot maintain cell turgidity and biochemical activity (Brown 1995).

A research project was conducted to determine the frequency and periodicity of water stress in perennial rangeland plants of western North Dakota. Plant water stress develops in plant tissue during growing season months with water deficiency conditions. The frequency, or rate of occurrence, of water stress conditions affects the percentage of total potential quantity and quality of herbage biomass produced by plants and the periodicity, or rate of reoccurrence, of water stress conditions affects the percentage of time that plant production is limited during growing season months.

Procedures

Monthly periods with water deficiency can be identified by the ombrothermic diagram technique reported by Emberger et al. (1963). This method graphs mean monthly temperature (°C) and monthly precipitation (mm) on the same axis, with the scale of the precipitation data at twice that of the temperature data. The resulting ombrothermic diagram shows monthly periods in which precipitation is greater than the evapotranspiration rate set by the mean monthly temperature and identifies monthly periods with water deficiency conditions, unfavorable periods during which perennial plants experience water stress. Water deficiency exists during months when the precipitation data bar drops below the temperature data curve. Ombrothermic diagrams were developed from historical climatological data of temperature and precipitation collected during the 118 year period from 1892 through 2009 at the Dickinson Research Extension Center, latitude 46° 53' N, longitude 102° 49' W, elevation 2,500 feet, Dickinson, North Dakota, USA.

Results and Discussion

The long-term (118 year) mean annual temperature was 40.9° F. January was the coldest month, with a mean temperature of 11.5° F. July and August were the warmest months, with mean temperatures of 68.8° F and 67.0° F, respectively (table 1). Perennial grassland plants are capable of active growth for periods longer than the frost-free period. The growing season for perennial plants was considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with the mean daily temperature at or above 32° F. In western North Dakota, the growing season for perennial plants was considered to be generally from mid April through mid October (6.0 months). The long-term mean annual precipitation was 16.0 inches (table 1). The growing season precipitation (April to October) was 13.5 inches, 84.5% of the annual precipitation. The early portion of the growing season (April to July) received 9.5 inches, 59.5% of the annual precipitation and the latter portion of the growing season (August to October) received 4.0 inches, 25.0% of the annual precipitation. Total precipitation received during the nongrowing season (November through March) was only 2.5 inches, 15.6% of the annual precipitation (table 2).

The long-term (118 year) ombrothermic diagram (figure 1) showed near water deficiency conditions during August, September, and October, a finding indicating that rangeland plants generally had difficulty growing and accumulating biomass during these 3 months. Favorable water relations occurred during April, May, June, and July, a period during which rangeland plants were capable of growing and accumulating herbage biomass.

The monthly ombrothermic diagrams for 118 years, 1892 to 2009, were reported in Manske (2010). Simplified representations of the ombrothermic water deficiency data were placed in table 3a, b, c. The first score of years, 1890 to 1909, with 18 years of data, had 43.0 growing season months with water deficiency conditions, 39.8%, for a mean of 2.4 months with water deficiency per growing season (table 3a). The second score of years, 1910 to 1929, had 34.0 growing season months with water deficiency conditions, 28.3%, for a mean of 1.7 months with water deficiency per growing season (table 3a). The third score of years, 1930 to 1949, had 43.5 growing season months with water deficiency conditions, 36.3%, for a mean of 2.2 months with water deficiency per growing season (table 3b). The fourth score of years, 1950 to 1969, had 37.0 growing season months with water deficiency conditions, 30.8%, for a mean of 1.9 months with water deficiency per growing season (table 3b). The fifth score of years, 1970 to 1989, had 37.5 growing season months with water deficiency conditions, 31.3%, for a mean of 1.9 months with water deficiency per growing season (table 3c). The sixth score of years, 1990 to 2009, had 36.5 growing season months with water deficiency conditions, 30.4%, for a mean of 1.8 months with water deficiency per growing season (table 3c). The 118 year period, 1892 to 2009, had 231.5 growing season months with water deficiency conditions, 32.7%, for a long-term mean of 2.0 months with water deficiency per growing season (table 3a, b, c).

Growing seasons that had no months with water deficiency conditions occurred seven times, 1912, 1920, 1941, 1951, 1982, 1985, and 1998, 5.9%, for a long-term mean of about 1 growing season without water deficiency in 16.9 years (table 3a, b, c).

Precipitation levels during an entire growing season compared to the long-term mean for 118 years separated growing seasons into dry, wet, or normal categories. Dry growing seasons received less than 75% of the long-term mean precipitation. Growing seasons with precipitation amounts at less than 75% and greater than 50% of the long-term mean were considered to have moderate drought conditions. Growing seasons with precipitation amounts at less than 50% of the long-term mean were considered to have severe drought conditions. Wet growing seasons received greater than 125% of the long-term mean precipitation. Growing seasons with precipitation amounts at greater than 125% and less than 150% of the long-term mean were considered to have moderate wet conditions. Growing seasons with precipitation amounts at greater than 150% of the long-term mean were considered to have extreme wet conditions. Normal growing seasons received greater than 75% and less than 125% of the long-term mean precipitation.

The first score of years, 1890 to 1909, with 18 years of data, had 5 dry growing seasons, 27.8%, for a mean of 1 dry growing season in 3.6 years. All 5 dry growing seasons had moderate drought conditions (table 3a). The second score of years, 1910 to 1929, had 3 dry growing seasons, 15.0%, for a mean of 1 dry growing season in 6.7 years. Two dry growing seasons had moderate drought conditions and one dry growing season, 1919, had severe drought conditions (table 3a). The third score of years, 1930 to 1949, had 5 dry growing seasons, 25.0%, for a mean of 1 dry growing season in 4.0 years. Three dry growing seasons had moderate drought conditions and two dry growing seasons, 1934 and 1936, had severe drought conditions (table 3b). The fourth score of years, 1950 to 1969, had 3 dry growing seasons, 15.0%, for a mean of 1 dry growing season in 6.7 years. All three dry growing seasons had moderate drought conditions (table 3b). The fifth score of years, 1970 to 1989, had 1 dry growing season, 5.0%, for a mean of 1 dry growing season in 20.0 years. The one dry growing season, 1988, had severe drought conditions (table 3c). The sixth score of years, 1990 to 2009, had 1 dry growing season, 5.0%, for a mean of 1 dry growing season in 20.0 years. The one dry growing season had moderate drought conditions (table 3c). The 118 year period, 1892 to 2009, had 18 dry growing seasons, 15.3%, for a mean of 1 dry growing season in 6.6 years. Fourteen dry growing seasons had moderate drought conditions, 11.9%, for a mean of 1 growing season with moderate drought conditions in 8.4 years, and four dry growing seasons, 1919, 1934, 1936, and 1988, had severe drought conditions, 3.4%, for a mean of 1 growing season with severe drought conditions in 29.5 years.

The first score of years, 1890 to 1909, with 18 years of data, had 1 wet growing season, 5.6%, for a mean of 1 wet growing season in 18.0 years. The one wet growing season had moderate wet conditions (table 3a). The second score of years, 1910 to 1929, had 4 wet growing seasons, 20.0%, for a mean of 1 wet growing season in 5.0 years. Three wet growing seasons had moderate wet conditions and one wet growing season, 1914, had extreme wet conditions (table 3a). The third score of years, 1930 to 1949, had 3 wet growing seasons, 15.0%, for a mean of 1 wet growing season in 6.7 years. Two wet growing seasons had moderate wet conditions and one wet growing season, 1941, had extreme wet conditions (table 3b). The fourth score of years, 1950 to 1969, had 4 wet growing seasons, 20.0%, for a mean of 1 wet growing season in 5.0 years. All four wet growing seasons had moderate wet conditions (table 3b). The fifth score of years, 1970 to 1989, had 6 wet growing seasons, 30.0%, for a mean of 1 wet growing season in 3.3 years. Five wet growing seasons had moderate wet conditions and one wet growing season, 1982, had extreme wet conditions (table 3c). The sixth score of years, 1990 to 2009, had 3 wet growing seasons, 15.0%, for a mean of 1 wet growing season in 6.7 years. Two wet growing seasons had moderate wet conditions and one wet growing season, 1998, had extreme wet conditions (table 3c). The 118 year period, 1892 to 2009, had 21 wet growing seasons, 17.8%, for a mean of 1 wet growing season in 5.6 years. Seventeen wet growing seasons had moderate wet conditions, 14.4%, for a mean of 1 growing season with moderate wet conditions in 6.9 years, and four wet growing seasons, 1914, 1941, 1982, and 1998, had extreme wet conditions, 3.4%, for a mean of 1 growing season with extreme wet conditions in 29.5 years.

The first score of years, 1890 to 1909, with 18 years of data, had 12 normal growing seasons, 66.7%, for a mean of 1 normal growing season in 1.5 years (table 3a). The second score of years, 1910 to 1929, had 13 normal growing seasons, 65.0%, for a mean of 1 normal growing season in 1.5 years (table 3a). The third score of years, 1930 to 1949, had 12 normal growing seasons, 60.0%, for a mean of 1 normal growing season in 1.7 years (table 3b). The fourth score of years, 1950 to 1969, had 13 normal growing seasons, 65.0%, for a mean of 1 normal growing season in 1.5 years (table 3b). The fifth score of years, 1970 to 1989, had 13 normal growing season, 65.0%, for a mean of 1 normal growing season in 1.5 years (table 3c). The sixth score of years, 1990 to 2009, had 16 normal growing seasons, 80.0%, for a mean of 1 normal growing season in 1.3 years (table 3c). The 118 year period, 1892 to 2009, had 79 normal growing seasons, 66.9%, for a mean of 1 normal growing season in 1.5 years.

The 118 year period, 1892 to 2009, had 231.5 growing season months with water deficiency conditions, 32.7%, for a mean of 2.0 months with water deficiency per growing season; this long-term period had 7.0 growing seasons with no water deficiency conditions, 5.9%, for a mean of 1 growing season without water deficiency months in 16.9 years; this long-term period had 18 growing seasons with dry conditions, 15.3%, for a mean of 1 dry growing season in 6.6 years; this long-term period had 21 growing seasons with wet conditions, 17.8%, for a mean of 1 wet growing season in 5.6 years; and this long-term period had 79 growing seasons with normal conditions, 66.9%, for a mean of 1 normal growing season in 1.5 years (table 4).

The periodicity, or rate of reoccurrence, of water deficiency conditions was not distributed evenly among the growing season months. April, May, June, and July received 59.5% of the annual precipitation and had 35.9% of the water deficiency months. August, September, and October received 25.0% of the annual precipitation and had 64.1% of the water deficiency months. Water deficiency months occurred in April, May, June, and July during 20 years (16.9%), 16 years (13.6%), 12 years (10.2%), and 45 years (38.1%) between 1892 and 2009, respectively (table 5). Water deficiency conditions occurred in August, September, and October during 62 years (52.5%), 59 years (50.0%), and 55 years (46.6%) during the 118 year period, respectively (table 5). August, September, and/or October had water deficiency conditions during 106 years, 89.8% of the past 118 years. Rangeland perennial plants produced most of their growth in leaf and flower stalk height (Goetz 1963) and in herbage biomass weight (Manske 1994) during May, June, and July because of the generally advantageous water conditions. The high periodicity of water deficiency conditions during August, September, and October limited rangeland plant growth and herbage biomass accumulation.

Conclusion

The average 6 month perennial plant growing season, mid April to mid October, had water deficiency conditions during 2 months, 32.7%. These periods with precipitation shortages were the normal weather conditions for western North Dakota. Growing seasons without water deficiency conditions were actually the abnormal phenomenon and occurred during only 5.9% of the growing seasons. Growing seasons with dry conditions occurred during 15.3% of the years; growing seasons with moderate drought conditions occurred during 11.9% of the years; and growing seasons with severe drought conditions occurred during 3.4% of the years. Growing seasons with wet conditions occurred during 17.8% of the years; growing seasons with moderate wet conditions occurred during 14.4% of the years; and growing seasons with extreme wet conditions occurred during 3.4% of the years. Growing seasons with normal conditions occurred during 66.9% of the years during the 118 year period from 1892 to 2009. May, June, and July had water deficiency conditions 13.6%, 10.2%, and 38.1% of the time, respectively. August, September, and October had water deficiency conditions 52.5%, 50.0%, and 46.6% of the time, respectively. Water deficiency conditions reoccurred at a mean rate of 19.7% during the early portion of the growing season (April-July) and reoccurred at a mean rate of 49.7% during the latter portions of the growing season (August-October). Water deficiency conditions during growing season months caused water stress in perennial rangeland plants that limited herbage biomass growth in quantity and quality that, subsequently, resulted in reduced livestock weight production. Implementation of the twice-over rotation system which is a biologically effective grazing management strategy that activates compensatory physiological processes, activates vegetative reproduction of secondary tillers from axillary buds, and stimulates soil organism activity in the rhizosphere reduces the negative impacts caused from plant water stress by increasing plant density, reducing soil temperature, reducing evaporation of soil water, improving soil structure and water infiltration, improving soil water holding capacity, and increasing available soil mineral nitrogen to levels greater than one hundred pounds per acre.

Table 1. Long-term mean temperature and precipitation.				
		Mean Monthly Temperature		Monthly Precipitation
		°F		inches
	Jan	11.47		0.41
	Feb	15.28		0.41
	Mar	26.18		0.74
	Apr	41.54		1.41
	May	52.79		2.33
	Jun	61.96		3.55
	Jul	68.75		2.23
	Aug	67.00		1.72
	Sep	56.11		1.32
	Oct	43.70		0.96
	Nov	28.45		0.53
	Dec	16.94		0.41
	Mean	40.85 °F	Total	16.00 inches

Table 2. Seasonal precipitation distribution.			
		Inches	Percent
	Average Annual Precipitation	16.00	
	Growing Season (Apr-Oct)	13.52	(84.50%)
	Apr, May, Jun, Jul	9.52	(59.50%)
	Aug, Sep, Oct	4.00	(25.00%)
	Nongrowing Season (Nov-Mar)	2.50	(15.63%)

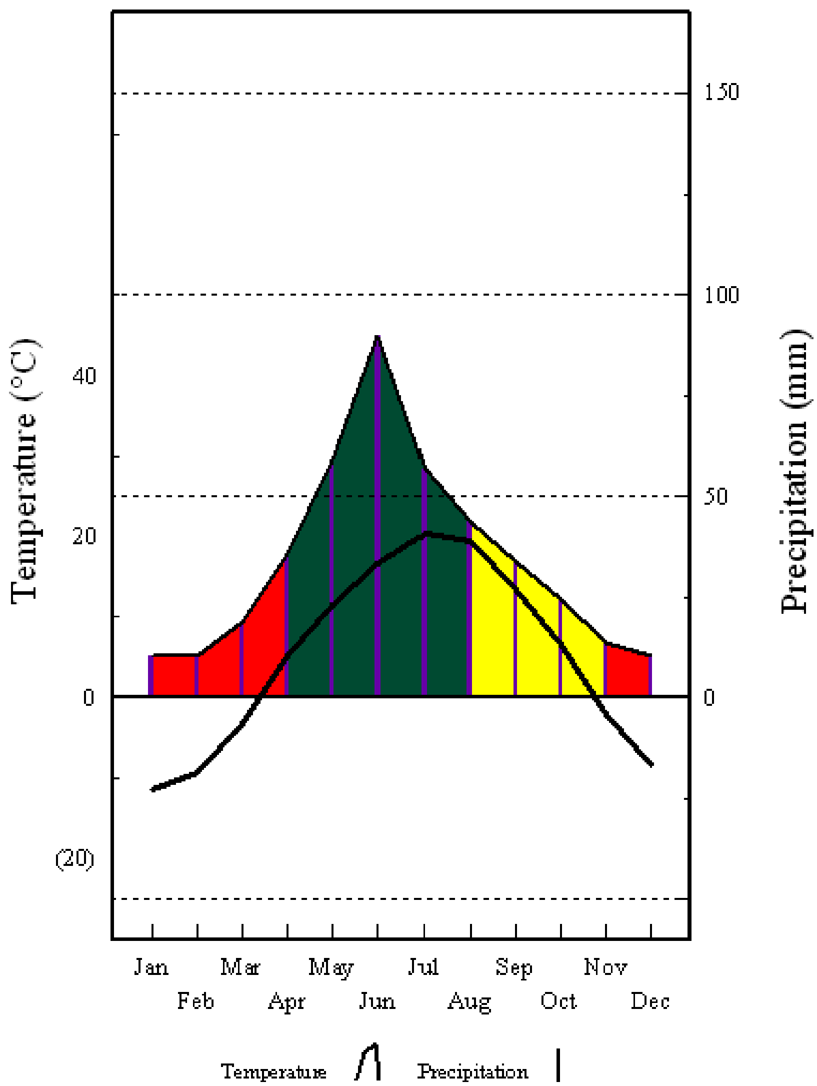
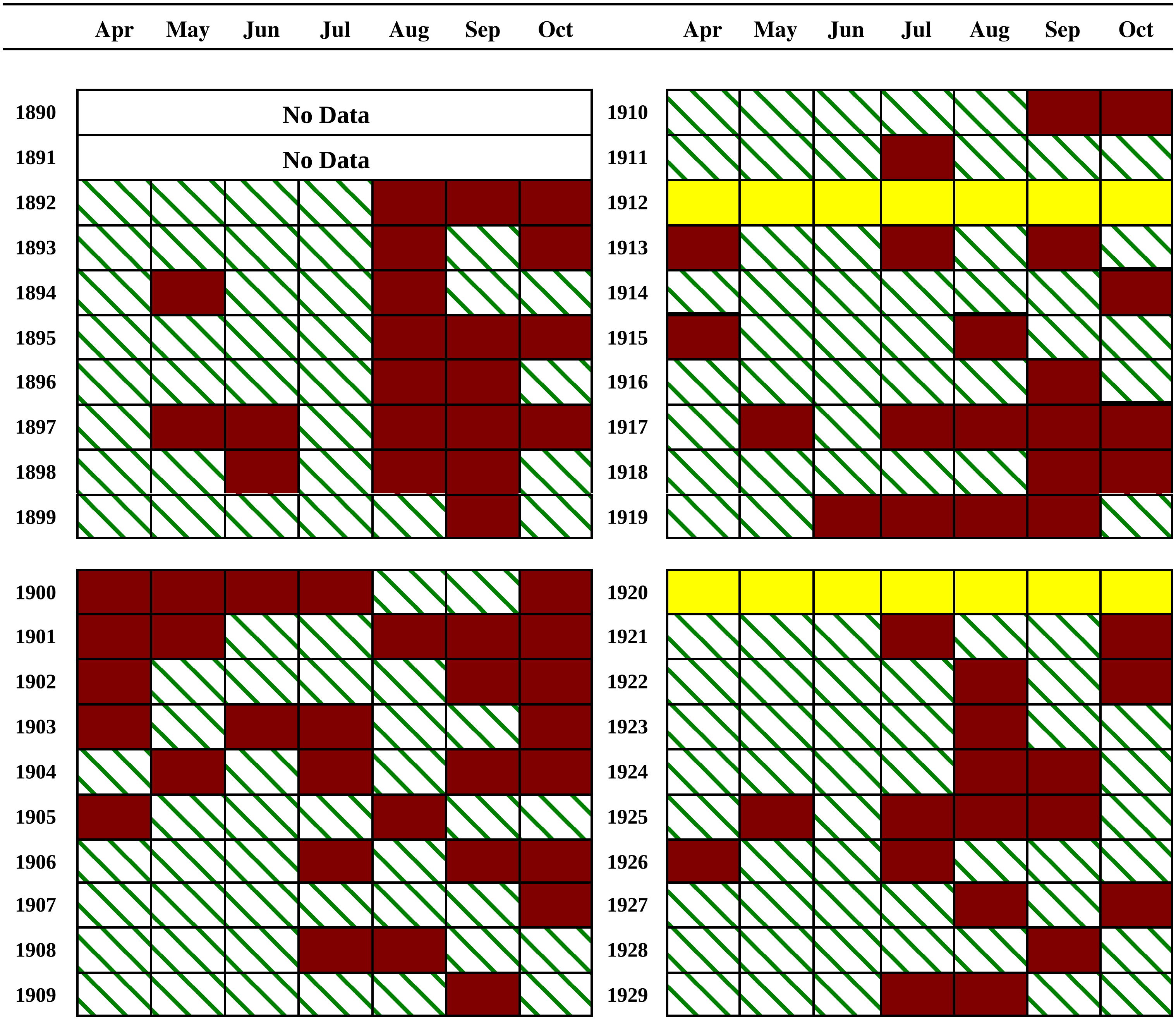


Fig. 1. Ombrothermic diagram of long-term (1892-2009) mean monthly temperature and monthly precipitation at Dickinson, North Dakota.

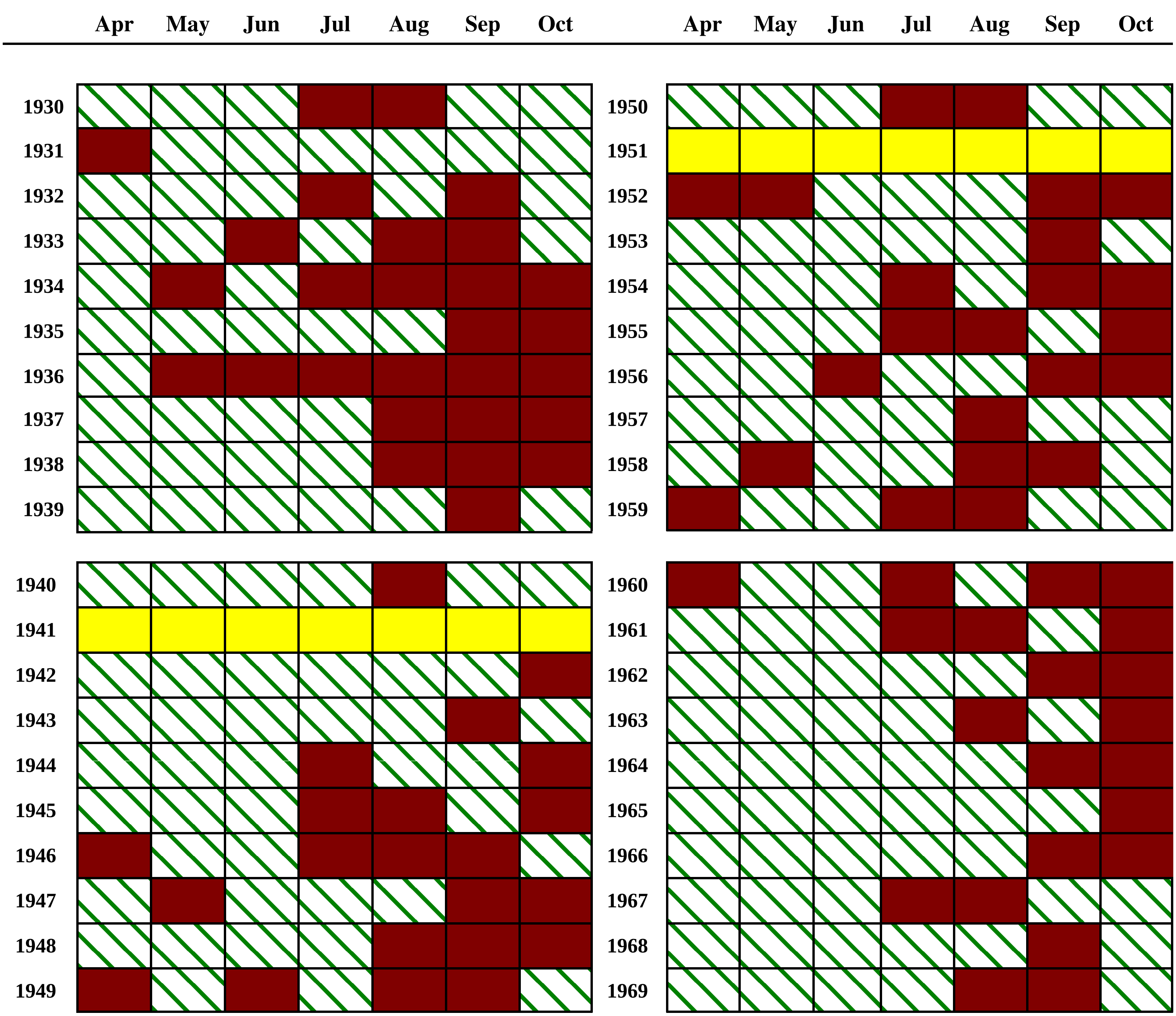
Table 3a. Growing season months with water deficiency conditions that caused water stress in perennial plants.



1892-1909 18 Years		
Months with water deficiency	39.8%	2.4 months/yr
Years with no water deficiency	0.0%	0 yr in 18 yrs
Dry growing seasons	27.8%	1 yr in 3.6 yrs
Wet growing seasons	5.6%	1 yr in 18 yrs
Normal growing seasons	66.7%	1 yr in 1.5 yrs

1910-1929 20 Years		
Months with water deficiency	28.3%	1.7 months/yr
Years with no water deficiency	10.0%	1 yr in 10 yrs
Dry growing seasons	15.0%	1 yr in 6.7 yrs
Wet growing seasons	20.0%	1 yr in 5 yrs
Normal growing seasons	65.0%	1 yr in 1.5 yrs

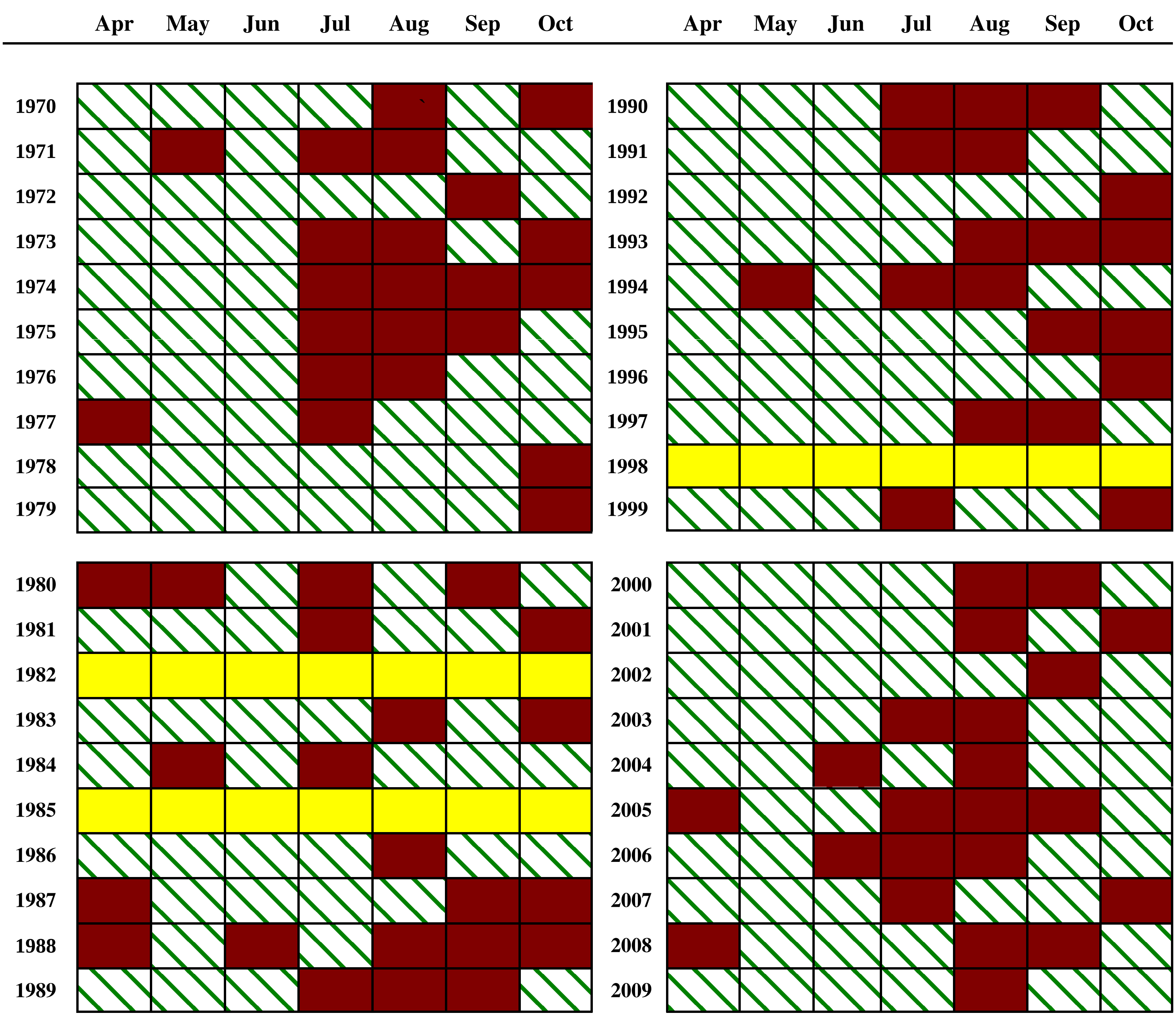
Table 3b. Growing season months with water deficiency conditions that caused water stress in perennial plants.



	1930-1949 20 Years			1950-1969 20 Years		
	Months with water deficiency	36.3%	2.2 months/yr	Months with water deficiency	30.8%	1.9 months/yr
	Years with no water deficiency	5.0%	1 yr in 20 yrs	Years with no water deficiency	5.0%	1 yr in 20 yrs
	Dry growing seasons	25.0%	1 yr in 4 yrs	Dry growing seasons	15.0%	1 yr in 6.7 yrs
	Wet growing seasons	15.0%	1 yr in 6.7 yrs	Wet growing seasons	20.0%	1 yr in 5 yrs

Normal growing seasons	60.0%	1 yr in 1.7 yrs	Normal growing seasons	65.0%	1 yr in 1.5 yrs

Table 3c. Growing season months with water deficiency conditions that caused water stress in perennial plants.



1970-1989 20 Years			**1990-2009 20 Years**		
Months with water deficiency	31.3%	1.9 months/yr	Months with water deficiency	30.4%	1.8 months/yr
Years with no water deficiency	10.0%	1 yr in 10 yrs	Years with no water deficiency	5.0%	1 yr in 20 yrs
Dry growing seasons	5.0%	1 yr in 20 yrs	Dry growing seasons	5.0%	1 yr in 20 yrs

Wet growing seasons	30.0%	1 yr in 3.3 yrs	Wet growing seasons	15.0%	1 yr in 6.7 yrs
Normal growing seasons	65.0%	1 yr in 1.5 yrs	Normal growing seasons	80.0%	1 yr in 1.3 yrs

Table 4. Summary of water stress conditions.

1892 to 2009	118 years	
Months with Water Deficiency	32.7%	2.0 months/year
Growing Seasons with no Water Deficiency	5.9%	1 yr in 16.9 years
Dry Growing Seasons	15.3%	1 yr in 6.6 years
Wet Growing Seasons	17.8%	1 yr in 5.6 years
Normal Growing Seasons	66.9%	1 yr in 1.5 years

Table 5. Periodicity of percent frequency of water deficiency occurring during growing season months.

April	May	June	July	August	September	October
16.9%	13.6%	10.2%	38.1%	52.5%	50.0%	46.6%

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