RANGE RESEARCH REPORT

Range Plant Growth Related to Climatic Factors of Western North Dakota, 1982-2020

North Dakota State University
Dickinson Research Extension Center

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Introduction

Successful long-term management of grassland ecosystems requires knowledge of the relationships of range plant growth and regional climatic factors. Range plant growth and development are regulated by climatic conditions. Length of daylight, temperature, precipitation, and water deficiency are the most important climatic factors that affect rangeland plants (Manske 2011).

Light

Light is necessary for plant growth because light is the source of energy for photosynthesis. Plant growth is affected by variations in quality, intensity, and duration of light. The quality of light (wavelength) varies from region to region, but the quality of sunlight does not vary enough in a given region to have an important differential effect on the rate of photosynthesis. However, the intensity (measurable energy) and duration (length of day) of sunlight change with the seasons and affect plant growth. Light intensity varies greatly with the season and with the time of day because of changes in the angle of incidence of the sun's rays and the distance light travels through the atmosphere. Light intensity also varies with the amount of humidity and cloud cover because atmospheric moisture absorbs and scatters light rays.

The greatest variation in intensity of light received by range plants results from the various degrees of shading from other plants. Most range plants require full sunlight or very high levels of sunlight for best growth. Shading from other plants reduces the intensity of light that reaches the lower leaves of an individual plant. Grass leaves grown under shaded conditions become longer but narrower, thinner (Langer 1972, Weier et al. 1974), and lower in weight than leaves in sunlight (Langer 1972). Shaded leaves have a reduced rate of photosynthesis, which decreases the carbohydrate supply and causes a reduction in growth rate of leaves and roots (Langer 1972). Shading increases the rate of senescence in lower, older leaves. Accumulation of standing dead leaves ties up carbon and nitrogen. Decomposition of leaf material through microbial activity can take place only after the leaves have made contact with the soil. Standing dead material not in contact with the soil does not decompose but breaks down slowly as a result of leaching and weathering. Under ungrazed treatments the dead leaves remain standing for several years, slowing nutrient cycles, restricting nutrient supply, and reducing soil microorganism activity in the top 12 inches of soil. Standing dead leaves shade early leaf growth in spring and therefore slow the rate of growth and reduce leaf area. Long-term effects of shading, such as that occurring in ungrazed grasslands and under shrubs or leafy spurge, reduce the native grass species composition and increase composition of shade-tolerant or shade-adapted replacement species like smooth bromegrass and Kentucky bluegrass.

Day-length period (photoperiod) is one of the most dependable cues by which plants time their activities in temperate zones. Day-length period for a given date and locality remains the same from year to year. Changes in the photoperiod function as the timer or trigger that activates or stops physiological processes bringing about growth and flowering of plants and that starts the process of hardening for resistance to low temperatures in fall and winter. Sensory receptors, specially pigmented areas in the buds or leaves of a plant, detect day length and night length and can activate one or more hormone and enzyme systems that bring about physiological responses (Odum 1971, Daubenmire 1974, Barbour et al. 1987).

The phenological development of rangeland plants is triggered by changes in the length of daylight. Vegetative growth is triggered by photoperiod and temperature (Langer 1972, Dahl 1995), and reproductive initiation is triggered primarily by photoperiod (Roberts 1939, Langer 1972, Leopold and Kriedemann 1975, Dahl 1995) but can be slightly modified by temperature and precipitation (McMillan 1957, Leopold and Kriedemann 1975, Dahl and Hyder 1977, Dahl 1995). Some plants are long-day plants and others are short-day plants. Long-day plants reach the flower phenological stage after exposure to a critical photoperiod and during the period of increasing daylight between mid April and mid June. Generally, most cool-season plants with the C_3 photosynthetic pathway are long-day plants and reach flower phenophase before 21 June. Short-day plants are induced into flowering by day lengths that are shorter than a critical length and that occur during the period of decreasing day length after mid June. Short-day plants are technically responding to the increase in the length of the night period rather than to the decrease in the day length (Weier et al. 1974, Leopold and Kriedemann 1975). Generally, most warm-season plants with the C_4 photosynthetic pathway are short-day plants and reach flower phenophase after 21 June.

The annual pattern in the change in daylight duration follows the seasons and is the same every year for each region. Grassland management strategies based on phenological growth stages of the major grasses can be planned by calendar date after the relationships between phenological stage of growth of the major grasses and time of season have been determined for a region.

Temperature

Temperature is an approximate measurement of the heat energy available from solar radiation. At both low and high levels temperature limits plant growth. Most plant biological activity and growth occur within only a narrow range of temperatures, between 32º F (0° C) and 122º F (50º C) (Coyne et al. 1995). Low temperatures limit biological reactions because water becomes unavailable when it is frozen and because levels of available energy are inadequate. However, respiration and photosynthesis can continue slowly at temperatures well below 32º F if plants are "hardened". High temperatures limit biological reactions because the complex structures of proteins are disrupted or denatured.

Periods with temperatures within the range for optimum plant growth are very limited in western North Dakota. The frost-free period is the number of days between the last day with minimum temperatures below 32º F (0º C) in the spring and the first day with minimum temperatures below 32º F (0º C) in the fall and is approximately the length of the growing season for annually seeded plants. The frost-free period for western North Dakota generally lasts for 120 to 130 days, from mid to late May to mid to late September (Ramirez 1972). Perennial grassland plants are capable of growing for periods longer than the frost-free period, but to continue active growth they require temperatures above the level that freezes water in plant tissue and soil. Many perennial plants begin active growth more than 30 days before the last frost in spring and continue growth after the first frost in fall. The growing season for perennial plants is considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with mean daily temperature at or above 32º F (0º C). In western North Dakota the growing season for perennial plants is considered to be generally from mid April through mid October. Low air temperature during the early and late portions of the growing season greatly limits plant growth rate. High temperatures, high evaporation rates, drying winds, and low precipitation levels after mid summer also limit plant growth.

Different plant species have different optimum temperature ranges. Cool-season plants, which are C_3 photosynthetic pathway plants, have an optimum temperature range of 50° to 77°F (10° to 25°C). Warm-season plants, which are C_4 photosynthetic pathway plants, have an optimum temperature range of 86° to 105°F (30° to 40°C) (Coyne et al. 1995).

Water (Precipitation)

Water, an integral part of living systems, is ecologically important because it is a major force in shaping climatic patterns and biochemically important because it is a necessary component in physiological processes (Brown 1995). Water is the principal constituent of plant cells, usually composing over 80% of the fresh weight of herbaceous plants. Water is the primary solvent in physiological processes by which gases, minerals, and other materials enter plant cells and by which these materials are translocated to various parts of the plant. Water is the substance in which processes such as photosynthesis and other biochemical reactions occur and a structural component of proteins and nucleic acids. Water is also essential for the maintenance of the rigidity of plant tissue and for cell enlargement and growth in plants (Brown 1977, Brown 1995).

Water Deficiency

Temperature and precipitation act together to affect the physiological and ecological status of range plants. The biological situation of a plant at any time is determined by the balance between rainfall and potential evapotranspiration. The higher the temperature, the greater the rate of evapotranspiration and the greater the need for rainfall to maintain homeostasis. When the amount of rainfall received is less than potential evapotranspiration demand, a water deficiency exists. Evapotranspiration demand is greater than precipitation in the mixed grass and short grass prairie regions. The tall grass prairie region has greater precipitation than evapotranspiration demand. Under water deficiency conditions, plants are unable to absorb adequate water to match the transpiration rate, and plant water stress develops. Range plants have mechanisms that help reduce the damage from water stress, but some degree of reduction in herbage production occurs.

Plant water stress limits growth. Plant water stress develops in plant tissue when the rate of water loss through transpiration exceeds the rate of water absorption by the roots. 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 (Brown 1995).

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).

Study Area

The study area is the region around the Dickinson Research Extension Center (DREC) Ranch, Dunn County, western North Dakota, USA. Native vegetation in western North Dakota is the Wheatgrass-Needlegrass Type (Barker and Whitman 1988, Shiflet 1994) of the mixed grass prairie.

The climate of western North Dakota has changed several times during geologic history (Manske 1999). The most recent climate change occurred about 5,000 years ago, to conditions like those of the present, with cycles of wet and dry periods. The wet periods have been cool and humid, with greater amounts of precipitation. A brief wet period occurred around 4,500 years ago. Relatively long periods of wet conditions occurred in the periods between 2,500 and 1,800 years ago and between 1,000 and 700 years ago. Recent short wet periods occurred in the years from 1905 to 1916, 1939 to 1947, and 1962 to 1978. The dry periods have been warmer, with reduced precipitation and recurrent summer droughts. A widespread, long drought period occurred between the years 1270 and 1299, an extremely severe drought occurred from 1863 through 1875, and other more recent drought periods occurred from 1895 to 1902, 1933 to 1938, and 1987 to 1992. The current climatic pattern in western North Dakota is cyclical between wet and dry periods and has existed for the past 5,000 years (Bluemle 1977, Bluemle 1991, Manske 1994a).

Procedures

Daylight duration data for the Dickinson location of latitude 46° 48' N, longitude 102° 48' W, were tabulated from daily sunrise and sunset time tables compiled by the National Weather Service, Bismarck, North Dakota.

Temperature and precipitation data were taken from historical climatological data collected at the Dickinson Research Extension Center Ranch, latitude 47° 14' N, longitude 102° 50' W, Dunn County, near Manning, North Dakota, 1982-2020.

A technique reported by Emberger et al. (1963) was used to develop water deficiency months data from historical temperature and precipitation data. The water deficiency months data were used to identify months with conditions unfavorable for plant growth. This method plots 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 temperature and precipitation data are plotted against an axis of time. The resulting ombrothermic diagram shows general monthly trends and identifies months with conditions unfavorable for plant growth. Water deficiency conditions exist during months when the precipitation data bar drops below the temperature data curve and plants are under water stress. Plants are under temperature stress when the temperature curve drops below the freezing mark (0° C).

Results and Discussion

Light

The tilt of the earth's axis in conjunction with the earth's annual revolution around the sun produces the seasons and changes the length of daylight in temperate zones. Dickinson (figure 1) has nearly uniform day and night lengths (12 hours) during only a few days, near the vernal and autumnal equinoxes, 20 March and 22 September, respectively, when the sun's apparent path crosses the equator as the sun travels north or south, respectively. The shortest day length (8 hours, 23 minutes) occurs at winter solstice, 21 December, when the sun's apparent path is farthest south of the equator. The longest day length (15 hours, 52 minutes) occurs at summer solstice, 21 June, when the sun's apparent path is farthest north of the equator. The length of daylight during the growing season (mid April to mid October) oscillates from about 13 hours in mid April, increasing to nearly 16 hours in mid June, then decreasing to around 11 hours in mid October (figure 1).

Temperature

The DREC Ranch in western North Dakota experiences severe, windy, dry winters with little snow accumulation. The springs are relatively moist in most years, and the summers are often droughty but are interrupted periodically by thunderstorms. The long-term (39-year) mean annual temperature is 42.1° F (5.7° C) (table 1). January is the coldest month, with a mean temperature of 14.8° F (-9.6° C). July and August are the warmest months, with mean temperatures of 69.6° F (20.9° C) and 68.4° F (20.2° C), respectively. Months with mean monthly temperatures below 32.0° F (0.0° C) are too cold for active plant growth. Low temperatures define the growing season for perennial plants, which is generally from mid April to mid October (6.0 months, 183 days). During the other 6 months each year, plants in western North Dakota cannot conduct active plant growth. Soils are frozen to a depth of 3 to 5 feet for a period of 4 months (121 days) (Larson et al. 1968). The early and late portions of the 6-month growing season have very limited plant activity and growth. The period of active plant growth is generally 5.5 months (168 days).

Western North Dakota has large annual and diurnal changes in monthly and daily air temperatures. The range of seasonal variation of average monthly temperatures between the coldest and warmest months is 55.0° F (30.5° C), and temperature extremes in western North Dakota have a range of 161.0° F (89.4° C), from the highest recorded summer temperature of 114.0° F (45.6° C) to the lowest recorded winter temperature of -47.0° F (-43.9° C). The diurnal temperature change is the difference between the minimum and maximum temperatures observed over a 24-hour period. The average diurnal temperature change during winter is 22.0° F (12.2° C), and the change during summer is 30.0° F (16.7° C). The average annual diurnal change in temperature is 26.0° F (14.4° C) (Jensen 1972). The large diurnal change in temperature during the growing season, which has warm days and cool nights, is beneficial for plant growth because of the effect on the photosynthetic process and respiration rates (Leopold and Kriedemann 1975).

Precipitation

The long-term (39-year) annual precipitation for the Dickinson Research Extension Center Ranch in western North Dakota is 17.11 inches (434.53 mm). The long-term mean monthly precipitation is shown in table 1. The growing-season precipitation (April to October) is 14.47 inches (367.45 mm) and is 84.57% of annual precipitation. June has the greatest monthly precipitation, at 3.15 inches (80.01 mm).

The seasonal distribution of precipitation (table 2) shows the greatest amount of precipitation occurring in the spring (7.14 inches, 41.73%) and the least amount occurring in winter (1.63 inches, 9.53%). Total precipitation received for the 5-month period of November through March averages less than 2.64 inches (15.43%). The precipitation received in the 3-month period of May, June, and July accounts for 47.17% of the annual precipitation (8.07 inches).

The annual and growing-season precipitation levels and percent of the long-term mean for 39 years (1982 to 2020) are shown in table 3. Drought conditions exist when precipitation amounts for a month, growing season, or annual period are 75% or less of the long-term mean. Wet conditions exist when precipitation amounts for a month, growing season, or annual period are 125% or greater of the long-term mean. Normal conditions exist when precipitation amounts for a month, growing season, or annual period are greater than 75% and less than 125% of the long-term mean. Between 1982-2020, 5 drought years (12.82%) (table 4) and 7 wet years (17.95%) (table 5) occurred. Annual precipitation amounts at normal levels, occurred during 27 years (69.23%) (table 3). The area experienced 5 drought growing seasons (12.82%) (table 6) and 7 wet growing seasons (17.95%) (table 7). Growing-season precipitation amounts at normal levels occurred during 27 years (69.23%) (table 3). The 6-year period (1987-1992) was a long period with near-drought conditions. The average annual precipitation for these 6 years was 12.12 inches (307.89 mm), only 70.84% of the long-term mean. The average growing-season precipitation for the 6-year period was 9.97 inches (253.11 mm), only 68.90% of the long-term mean (table 3).

Water Deficiency

Monthly periods with water deficiency conditions are identified on the annual ombrothermic graphs when the precipitation data bar drops below the temperature data curve. On the ombrothermic graphs, periods during which plants are under low-temperature stress are indicated when the temperature curve drops below the freezing mark of 0.0º C (32.0º F). The long-term ombrothermic graph for the DREC Ranch (figure 2) shows that near water deficiency conditions exist for August, September, and October. This finding indicates that range plants generally may have a difficult time growing and accumulating herbage biomass during these 3 months. Favorable water relations occur during May, June, and July, a condition indicating that range plants should be able to grow and accumulate herbage biomass during these 3 months.

The ombrothermic relationships for the Dickinson Research Extension Center Ranch in western North Dakota are shown for each month in table 8. The 39-year period (1982 to 2020) had a total of 234 months during the growing season. Of these growing-season months, 69.5 months had water deficiency conditions, which indicates that range plants were under water stress during 29.7% of the growing-season months (tables 8 and 9): this amounts to an average of 2.0 months during every 6.0-month growing season range plants have been limited in growth and herbage biomass accumulation because of water stress. The converse indicates that only 4.0 months of an average year have conditions in which plants can grow without water stress.

Most growing seasons have months with water deficiency conditions. In only 5 of the 39 years (table 8) did water deficiency conditions not occur in any of the six growing-season months. In each growing-season month of 1982, 2013, 2015, 2016, and 2019, the amounts and distribution of the precipitation were adequate to prevent water stress in plants. Nineteen years (48.72%) had water deficiency for 0.5 to 2.0 months during the growing season. Fourteen years (35.90%) had water deficiency conditions for 2.5 to 4.0 months during the growing season. One year (2.56%), 1988, had water deficiency conditions for 5.0 months during the growing season. None of the 39 years had water deficiency conditions for all 6.0 months of the growing season (table 8). The 6-year period (1987-1992) was a long period with low precipitation; during this period, water deficiency conditions existed for an average of 3.1 months during each growing season, which amounts to 51.33% of this period's growing-season months (table 8).

May, June, and July are the 3 most important precipitation months and therefore constitute the primary period of production for range plant communities. May and June are the 2 most important months for dependable precipitation. Only 4 (10.26%) of the 39 years had water deficiency conditions during May, and 4 years (12.82%) had water deficiency conditions during June. One year (2017) had water deficiency conditions in both May and June. Thirteen (33.33%) of the 39 years had water deficiency conditions in July (table 9). Only one year (2017) has had water deficiency conditions during May, June, and July (table 8b).

Most of the growth in range plants occurs in May, June, and July (Goetz 1963, Manske 1994b). Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time when plants have attained 100% of their growth in height (Manske 1994b). Range grass growth coincides with the 3-month period of May, June, and July, when 47.17% of the annual precipitation occurs.

August, September, and October are not dependable for positive water relations. August and September had water deficiency conditions in 46.15% and 51.28% of the years, respectively, and October had water deficiency conditions in 35.90% of the years (table 9). Visual observations of range grasses with wilted, senescent leaves in August indicate that most plants experience some level of water stress when conditions approach those of water deficiency. August, September, and/or October had water deficiency conditions during 82.05% of the growing seasons in the previous 39 years (table 8). These 3 months make up 42% of the growing season, and they had water deficiency conditions on the average of 45% of the time (table 9). The water relations in August, September, and October limit range plant growth and herbage biomass accumulation.

Over the last 39 years, drought years occurred 12.8% of the time. Drought growing seasons occurred 12.8% of the time. Water deficiency months occurred 29.7% of the time. Water deficiency occurred in May and June 10.3% and 12.8% of the time, respectively. July had water deficiency conditions 33.3% of the time. August, September, and October had water deficiency conditions more than 45% of the time. Water deficiency periods lasting for a month place plants under water stress severe enough to reduce herbage biomass production. These levels of water stress are a major factor limiting the quantity and quality of plant growth in western North Dakota and can limit livestock production if not considered during the development and implementation of long-term grazing management strategies.

The ombrothermic procedure to identify growing season months with water deficiency treats each month as an independent event. Precipitation during the other months of the year may buffer or enhance the degree of water stress experienced by perennial plants during water deficiency months. The impact of precipitation during other months on the months with water deficiency can be evaluated from annual running total precipitation data (table 10). Water deficiency conditions did not occur during any months in 2020 (table 10).

Conclusion

The vegetation in a region is a result of the total effect of the long-term climatic factors for that region. Ecologically, the most important climatic factors that affect rangeland plant growth are light, temperature, water (precipitation), and water deficiency.

Light is the most important ecological factor because it is necessary for photosynthesis. Changes in time of year and time of day coincide with changes in the angle of incidence of the sun's rays; these changes cause variations in light intensity. Daylight duration oscillation for each region is the same every year and changes with the seasons. Shading of sunlight by cloud cover and from other plants affects plant growth. Day-length period is important to plant growth because it functions as a trigger to physiological processes. Most cool-season plants reach flower phenophase between mid May and mid June. Most warm-season plants flower between mid June and mid September.

Plant growth is limited by both low and high temperatures and occurs within only a narrow range of temperatures, between 32º and 122º F. Perennial plants have a 6-month growing season, between mid April and mid October. Diurnal temperature fluctuations of warm days and cool nights are beneficial for plant growth. Cool-season plants have lower optimum temperatures for photosynthesis than do warm-season plants, and cool-season plants do not use water as efficiently as do warm-season plants. Temperature affects evaporation rates, which has a dynamic effect on the annual ratios of cool-season to warm-season plants in the plant communities. A mixture of cool- and warm-season plants is highly desirable because the grass species in a mixture of cool- and warm-season species have a wide range of different optimum temperatures and the herbage biomass production is more stable over wide variations in seasonal temperatures.

Water is essential for living systems. Average annual precipitation received at the DREC Ranch is 17.1 inches, with 84.6% occurring during the growing season and 47.2% occurring in May, June, and July. Plant water stress occurs when the rate of water loss through transpiration exceeds the rate of replacement by absorption. Years with drought conditions have occurred 12.8% of the time during the past 39 years. Growing seasons with drought conditions have occurred 12.8% of the time.

Water deficiencies exist when the amount of rainfall received is less than evapotranspiration demand. Temperature and precipitation data can be used in ombrothermic graphs to identify monthly periods with water deficiencies. During the past 39 years, 29.7% of the growing-season months had water deficiency conditions that placed range plants under water stress: range plants were limited in growth and herbage biomass accumulation for an average of 2.0 months during every 6-month growing season. May, June, and July had water deficiency conditions 10.3%, 12.8%, and 33.3% of the time, respectively. August, September, and October had water deficiency conditions 46.2%, 51.3% and 35.9% of the time, respectively. One month with water deficiency conditions causes plants to experience water stress severe enough to reduce herbage biomass production.

Most of the growth in range grasses occurs in May, June, and July. In western North Dakota, 100% of range grass leaf growth in height and 86% to 100% of range flower stalk growth in height are completed by 30 July. Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time during which plants are attaining 100% of their height. Most range grass growth occurs during the 3-month period of May, June, and July, when 47.2% of the annual precipitation occurs.

Grassland management should be based on phenological growth stages of the major grasses and can be planned by calendar date. Management strategies for a region should consider the climatic factors that affect and limit range plant growth.

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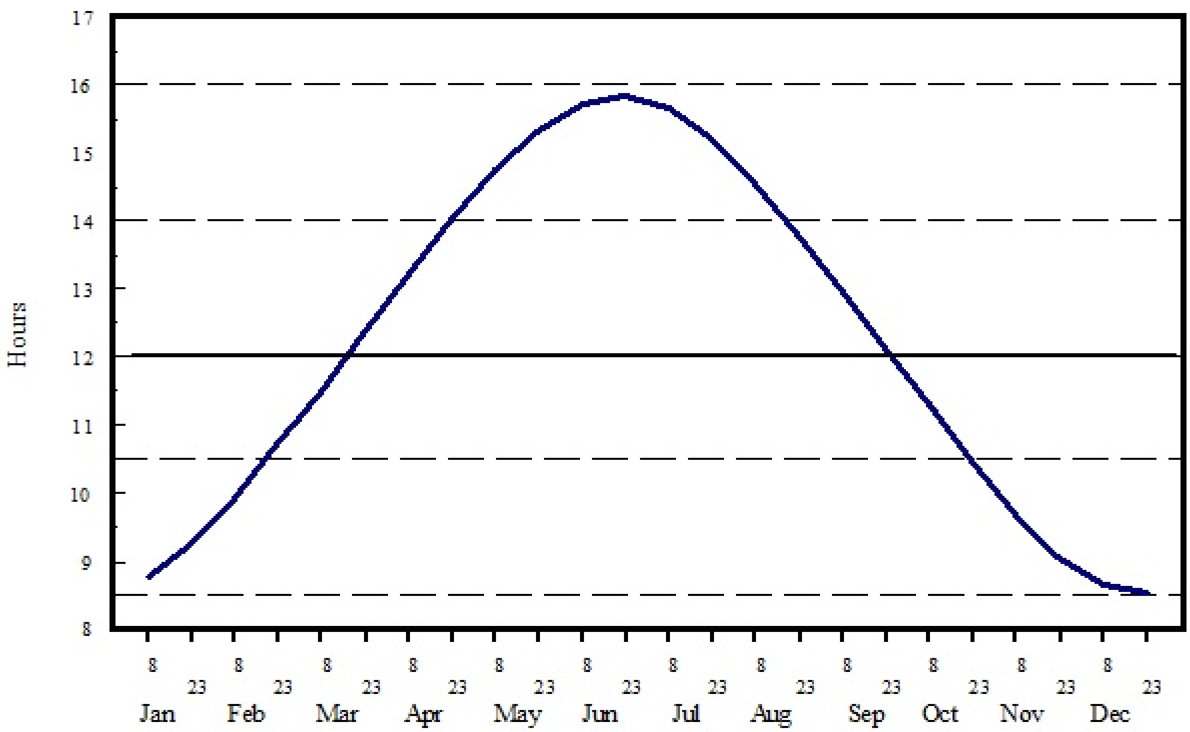

Figure. 1. Annual pattern of daylight duration at Dickinson, North Dakota.

Table 1. Long-term mean monthly temperature and monthly precipitation, 1982-2020.

	º F	º C	in.	mm
Jan	14.76	-9.58	0.44	11.09
Feb	18.35	-7.58	0.44	11.28
Mar	29.29	-1.51	0.75	19.10
Apr	41.48	5.27	1.41	35.73
May	53.58	11.99	2.58	65.55
Jun	63.22	17.34	3.15	80.01
Jul	69.60	20.89	2.34	59.40
Aug	68.40	20.22	2.01	50.99
Sep	56.15	13.87	1.68	42.77
Oct	43.61	6.45	1.30	33.01
Nov	29.21	-1.55	0.54	13.78
Dec	17.93	-7.81	0.47	11.82
	MEAN		**TOTAL**	
	42.13	**5.67**	**17.11**	**434.53**

Table 2. Seasonal precipitation distribution, 1982-2020.

Season	in.	%
Winter (Jan, Feb, Mar)	1.63	9.53
Spring (Apr, May, Jun)	7.14	41.73
Summer (Jul, Aug, Sep)	6.03	35.24
Fall (Oct, Nov, Dec)	2.31	13.50
TOTAL	**17.11**	

Table 3. Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2020.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2020	1.41	2.58	3.15	2.34	2.01	1.68	1.30	14.47	17.11
1982	1.37	2.69	4.30	3.54	1.75	1.69	5.75	21.09	25.31
% of LTM	97.16	104.26	136.51	151.28	87.06	100.60	442.31	145.78	147.95
1983	0.21	1.53	3.26	2.56	4.45	0.86	0.72	13.59	15.55
% of LTM	14.89	59.30	103.49	109.40	221.39	51.19	55.38	93.94	90.90
1984	2.87	0.00	5.30	0.11	1.92	0.53	0.96	11.69	12.88
% of LTM	203.55	0.00	168.25	4.70	95.52	31.55	73.85	80.81	75.29
1985	1.24	3.25	1.58	1.07	1.84	1.69	2.13	12.80	15.13
% of LTM	87.94	125.97	50.16	45.73	91.54	100.60	163.85	88.48	88.44
1986	3.13	3.68	2.58	3.04	0.46	5.29	0.18	18.36	22.96
% of LTM	221.99	142.64	81.90	129.91	22.89	314.88	13.85	126.91	134.22
1987	0.10	1.38	1.15	5.39	2.65	0.78	0.08	11.53	14.13
% of LTM	7.09	53.49	36.51	230.34	131.84	46.43	6.15	79.70	82.60
1988	0.00	1.85	1.70	0.88	0.03	0.73	0.11	5.30	9.03
% of LTM	0.00	71.71	53.97	37.61	1.49	43.45	8.46	36.64	52.78
1989	2.92	1.73	1.63	1.30	1.36	0.70	0.96	10.60	13.07
% of LTM	207.09	67.05	51.75	55.56	67.66	41.67	73.85	73.27	76.40
1990	2.03	2.39	3.75	1.13	0.31	0.68	0.85	11.14	11.97
% of LTM	143.97	92.64	119.05	48.29	15.42	40.48	65.38	77.00	69.97
1991	1.97	1.16	3.95	1.43	0.55	2.17	1.31	12.54	13.30
% of LTM	139.72	44.96	125.40	61.11	27.36	129.17	100.77	86.68	77.74
1992	0.81	0.68	1.59	2.70	2.02	0.72	0.16	8.68	11.23
% of LTM	57.45	26.36	50.48	115.38	100.50	42.86	12.31	60.00	65.64
1993	1.41	1.71	4.57	5.10	1.24	0.18	0.05	14.26	17.36
% of LTM	100.00	66.28	145.08	217.95	61.69	10.71	3.85	98.57	101.48
1994	0.86	1.46	4.51	1.07	0.31	1.08	4.58	13.87	16.14
% of LTM	60.99	56.59	143.17	45.73	15.42	64.29	352.31	95.88	94.34

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2020.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2020	1.41	2.58	3.15	2.34	2.01	1.68	1.30	14.47	17.11
1995	1.01	4.32	0.68	4.62	3.16	0.00	0.67	14.46	16.24
% of LTM	71.63	167.44	21.59	197.44	157.21	0.00	51.54	99.95	94.93
1996	0.14	3.07	1.86	2.55	1.72	2.51	0.09	11.94	15.97
% of LTM	9.93	118.99	59.05	108.97	85.57	149.40	6.92	82.53	93.35
1997	2.89	0.95	5.02	5.41	0.76	1.75	0.78	17.56	18.61
% of LTM	204.96	36.82	159.37	231.20	37.81	104.17	60.00	121.38	108.78
1998	0.40	1.51	5.98	2.11	4.60	0.71	4.38	19.69	22.42
% of LTM	28.37	58.53	189.84	90.17	228.86	42.26	336.92	136.11	131.05
1999	1.10	4.93	1.59	1.80	2.70	2.40	0.00	14.52	15.56
% of LTM	78.01	191.09	50.48	76.92	134.33	142.86	0.00	100.37	90.95
2000	1.26	1.90	3.77	2.77	2.74	1.09	1.46	14.99	20.23
% of LTM	89.36	73.64	119.68	118.38	136.32	64.88	112.31	103.62	118.25
2001	2.70	0.53	6.36	4.87	0.00	1.94	0.00	16.40	18.03
% of LTM	191.49	20.54	201.90	208.12	0.00	115.48	0.00	113.36	105.39
2002	1.14	2.18	5.40	4.27	4.24	0.74	0.88	18.85	21.88
% of LTM	80.85	84.50	171.43	182.48	210.95	44.05	67.69	130.30	127.90
2003	1.30	4.34	1.42	2.03	0.82	2.37	0.74	13.02	19.12
% of LTM	92.20	168.22	45.08	86.75	40.80	141.07	56.92	90.00	111.76
2004	0.89	1.31	1.65	2.30	0.93	2.57	3.10	12.75	16.51
% of LTM	63.12	50.78	52.38	98.29	46.27	152.98	238.46	88.13	96.51
2005	0.96	6.01	6.05	0.60	1.52	0.50	1.96	17.60	21.51
% of LTM	68.09	232.95	192.06	25.64	75.62	29.76	150.77	121.66	125.73
2006	2.78	2.82	2.13	0.96	2.87	1.42	2.01	14.99	17.70
% of LTM	197.16	109.30	67.62	41.03	142.79	84.52	154.62	103.62	103.46
2007	1.58	4.64	1.80	1.05	0.78	0.76	0.26	10.87	13.94
% of LTM	112.06	179.85	57.14	44.87	38.81	45.24	20.00	75.14	81.48

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2020.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2020	1.41	2.58	3.15	2.34	2.01	1.68	1.30	14.47	17.11
2008	0.61	2.79	4.02	1.06	1.02	1.04	1.68	12.22	14.88
% of LTM	43.26	108.14	127.62	45.30	50.75	61.90	129.23	84.47	86.98
2009	1.49	2.47	3.84	3.24	0.95	1.15	1.95	15.09	17.89
% of LTM	105.67	95.74	121.90	138.46	47.26	68.45	150.00	104.31	104.57
2010	1.43	3.70	3.50	1.94	1.39	4.09	0.13	16.18	19.03
% of LTM	101.42	143.41	111.11	82.91	69.15	243.45	10.00	111.84	111.24
2011	1.66	6.87	2.15	2.33	2.70	1.76	0.44	17.91	21.28
% of LTM	117.73	266.28	68.25	99.57	134.33	104.76	33.85	123.80	124.39
2012	2.38	1.58	4.31	1.98	0.82	0.21	2.35	13.63	15.46
% of LTM	168.79	61.24	136.83	84.62	40.80	12.50	180.77	94.22	90.37
2013	1.05	7.55	2.23	2.13	2.81	2.44	3.35	21.56	23.22
% of LTM	74.47	292.64	70.79	91.03	139.80	145.24	257.69	149.03	135.73
2014	1.41	3.73	3.38	0.37	8.84	1.03	0.59	19.35	21.11
% of LTM	100.00	144.57	107.30	15.81	439.80	61.31	45.38	133.76	123.40
2015	0.60	1.65	4.68	2.87	1.69	1.35	1.96	14.80	17.01
% of LTM	42.55	63.95	148.57	122.65	84.08	80.36	150.77	102.30	99.43
2016	3.44	2.26	1.96	3.61	1.86	2.66	1.80	17.59	19.70
% of LTM	243.97	87.60	62.22	154.27	92.54	180.95	138.46	121.59	115.15
2017	1.30	0.84	1.27	0.72	2.67	2.28	0.08	9.16	10.55
% of LTM	92.20	32.56	40.32	30.77	132.84	135.71	6.15	63.32	61.67
2018	0.48	1.22	4.23	2.01	0.55	1.84	0.66	10.99	14.39
% of LTM	34.04	47.29	134.29	85.90	27.36	109.52	50.77	75.97	84.12
2019	1.35	2.52	2.60	1.61	4.70	9.10	1.26	23.14	25.88
% of LTM	95.74	97.67	82.54	68.80	233.83	541.67	96.92	159.95	151.28
2020	0.59	1.45	1.10	2.67	2.56	0.86	0.26	9.49	11.01
% of LTM	41.84	56.20	34.92	114.10	127.36	51.19	20.00	65.60	64.36

Table 4. Years with annual precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	%LTM
1	1988	52.78
2	2017	61.67
3	2020	64.36
4	1992	65.64
5	1990	69.97

Table 5. Years with annual precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	%LTM
1	2019	151.28
2	1982	147.95
3	2013	135.73
4	1986	134.22
5	1998	131.05
6	2002	127.90
7	2005	125.73

Table 6. Years with growing-season precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	%LTM
1	1988	36.64
2	1992	60.00
3	2017	63.32
4	2020	65.60
5	1989	73.27

Table 7. Years with growing-season precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	%LTM
1	2019	159.95
2	2013	149.03
3	1982	145.78
4	1998	136.11
5	2014	133.76
6	2002	130.30
7	1986	126.91

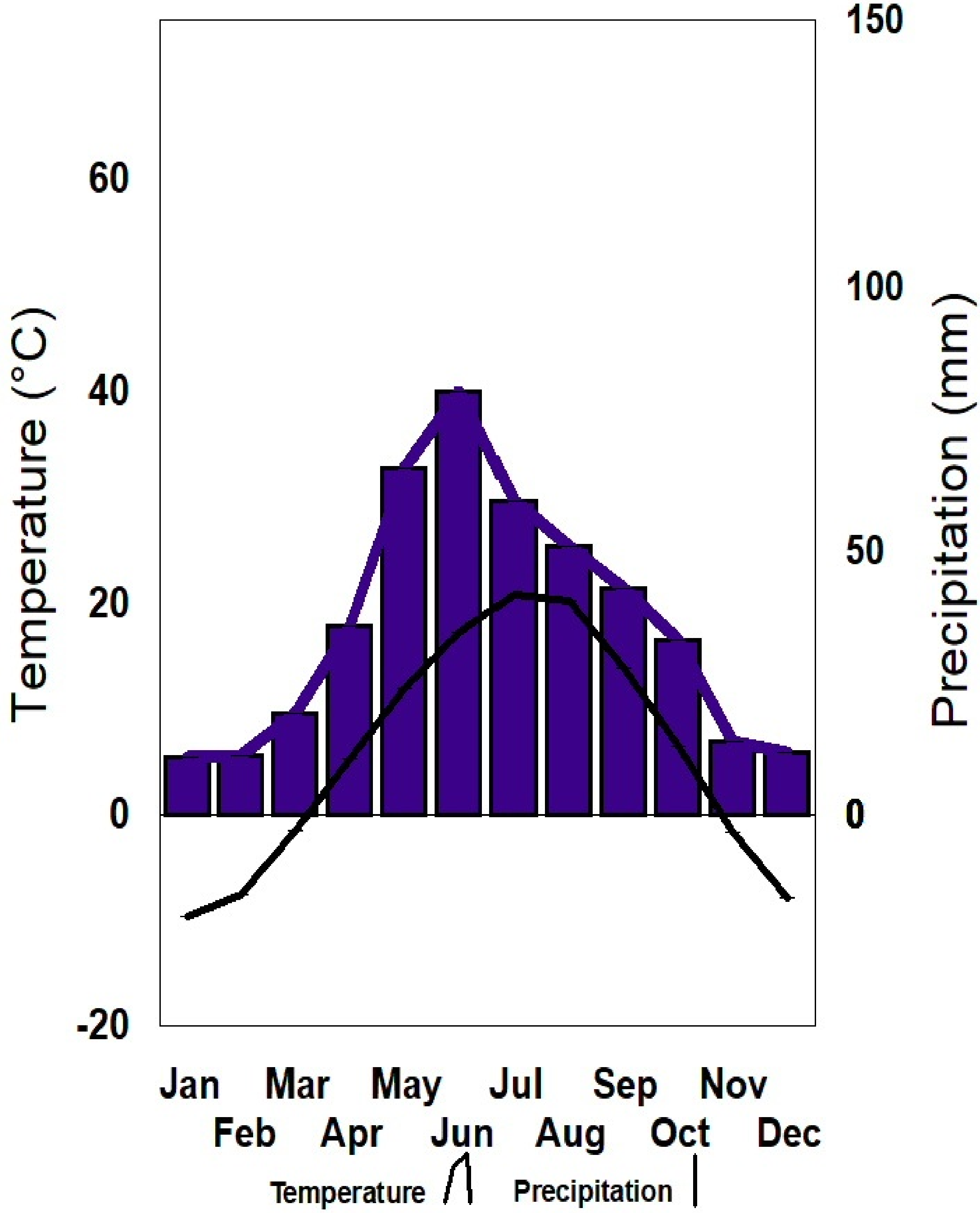

Figure 2. Ombrothermic diagram of long-term mean monthly temperature and monthly precipitation at the DREC Ranch, western North Dakota, 1982-2020.

Table 8a. Growing season months with water deficiency conditions that caused water stress in perennial plants (1982-1989, 1990-1999).

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
1980								-	-
1981	-	-				■		-	-
1982								0.0	0
1983	■					■		1.5	25
1984		■		■		■		3.0	50
1985				■				1.0	17
1986					■		■	1.5	25
1987	■		■			■	■	3.0	50
1988	■		■	■	■	■	■	5.0	83
1989				■	■	■		3.0	50
								18.0	**38**
1990				■	■	■		3.0	50
1991				■	■			2.0	33
1992		■				■	■	2.5	42
1993					■	■	■	2.5	42
1994				■	■	■		3.0	50
1995			■			■		2.0	33
1996	■						■	1.0	17
1997					■			1.0	7
1998	■					■		1.5	25
1999							■	0.5	8
								19.0	**32**

Table 8b. Growing season months with water deficiency conditions that caused water stress in perennial plants (2000-2009, 2010-2019).

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
2000						■		1.0	17
2001		■			■		■	2.5	42
2002						■		1.0	17
2003					■			1.0	17
2004					■			1.0	17
2005				■	■	■		3.0	50
2006				■				1.0	17
2007				■	■	■	■	3.5	58
2008				■	■	■		3.0	50
2009					■	■		2.0	33
								19.0	**32**
2010					■		■	1.5	25
2011							■	0.5	8
2012					■	■		2.0	33
2013								0.0	0
2014				■		■	■	2.5	42
2015								0.0	0
2016								0.0	0
2017		■	■	■			■	3.5	58
2018					■			1.0	17
2019								0.0	0
								11.0	**20**

Table 8b. Growing season months with water deficiency conditions that caused water stress in perennial plants (2020-2029, 2030-2039).

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
2020								2.5	42
2021									
2022									
2023									
2024									
2025									
2026									
2027									
2028									
2029									
								2.5	**4**
2030									
2031									
2032									
2033									
2034									
2035									
2036									
2037									
2038									
2039									

Table 9. Growing season months with water deficiency, 1982-2020.

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
TOTAL	5	4	5	13	18	20	14	69.5	30
% of 39 YEARS	12.8	10.3	12.8	33.3	46.2	51.3	35.9		

Table 10. Monthly precipitation and running total precipitation compared to the long-term mean (LTM), 2020.

	Monthly Precipitation (in)			Running Total Precipitation (in)		
Months	LTM 1982-2019	Precipitation 2020	% of LTM	Running LTM 1982-2019	Running Precipitation 2020	% of LTM
Jan	0.43	0.68	158.14	0.43	0.68	158.14
Feb	0.44	0.44	100.00	0.87	1.12	128.74
Mar	0.76	0.27	35.53	1.63	1.39	85.28
Apr	1.43	0.59	41.26	3.06	1.98	64.71
May	2.61	1.45	55.56	5.67	3.43	60.49
Jun	3.20	1.10	34.38	8.87	4.53	51.07
Jul	2.33	2.67	114.59	11.20	7.20	64.29
Aug	1.99	2.56	128.64	13.19	9.76	74.00
Sep	1.71	0.86	50.29	14.90	10.62	71.28
Oct	1.33	0.26	19.55	16.23	10.88	67.04
Nov	0.56	0.00	0.00	16.79	10.88	64.80
Dec	0.47	0.13	27.66	17.26	11.01	63.79
Total	17.26	11.01	63.79		11.01	63.79

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