Autecology of Prairie Plants on the Northern Mixed Grass Prairie

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Prairie ecosystems are complex; exceedingly more complex than the most complicated machines ever built by humans. The long-standing standard process to understand complex systems is to initially investigate the separate component parts. The gained knowledge of each part combined with the synergistic effects resulting when the parts work together provide the information needed to develop an understanding of the whole ecosystem. This classical concept of biological systems was developed by the Greek philosopher/scientist Aristotle (384-322 BC) who taught that "the whole is greater than the sum of its parts".

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component species and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains.

The prairie plants flourishing on northern mixed grass prairie ecosystems come with preprogramed genetic material that control the parameters of behavioral response, growth, and development of each particular species. All of these physiological factors are quantifiable. Six ecological studies conducted at the Dickinson Research Extension Center collected growth and development data on individual prairie plant species. These quantitative data were compiled in these reports and used to describe the distinctive annual growing season life histories of prairie species. The component species included in this study were grouped into three physiognomic categories: grasses and upland sedges, forbs, and shrubs and subshrubs.

Dr. Warren C. Whitman conducted a grass and sedge nutritional quality and phenological growth study with data collected weekly during the growing seasons of 1946 and 1947. The study included 1 upland sedge, 5 cool season, 4 warm season, 1 naturalized, and 2 domesticated grasses. The study sites were established in two seeded domesticated grasslands and a native rangeland pasture located about one mile (1.6 km) west of the original DREC livestock research units on the Dickinson campus (Whitman et al. 1951).

Dr. Warren C. Whitman originated and Dr. Harold Goetz completed a prairie plant growth in height and first flower date study with data collected on 7 to 10 day intervals during the growing seasons of 1955 to 1962. The study included 2 upland sedges, 8 cool season and 5 warm season grasses, 85 forbs, and 2 shrubs and 5 subshrubs. The study site was a 40 acre native rangeland pasture that had two hills and was located about one mile (1.6 km) northwest of the DREC main office on the Dickinson campus. The hills provided a gradient of soils that stratified into sandy, shallow, silty and clayey ecological sites creating various habitat characteristics for numerous species (Goetz 1963).

Dr. Nicholas Zaczkowski determined the range of flowering time of prairie plants during a floristic study in southwestern North Dakota. Daily records of observed flowering plants were reported on 7 to 8 day sampling periods during the growing seasons of 1969 to 1971. The study included 2 upland sedges, 1 naturalized, 3 cool season and 6 warm season grasses, 151 forbs, and 11 shrubs and 6 subshrubs. The study area included the vast complex of rolling prairie and badland terrain of southwestern North Dakota with sample sites located on most of the topographic positions that included sandy, shallow, silty, loamy terrace, deep sandy blowout, thin claypan, and shallow to scoria ecological sites (Zaczkowski 1972).

An autecological study of grasses and upland sedges was conducted by Dr. Llewellyn Manske during the growing seasons of 1983 to 1989 with data collected biweekly. The study included 1 upland sedge, 3 cool season, 2 warm season, 1 naturalized, and 2 domesticated grasses. The study sites were located at the Dickinson Research Extension Center ranch near Manning, ND, and consisted of two seeded domesticated grasslands and 720 acres of native rangeland pastures separated in three management treatments, each with two replications, and data collection sites established on sandy, shallow, and silty ecological sites. The ecological sites of the grazed treatments had matching paired plots, one grazed and the other with an ungrazed exclosure.

An autecological study of forbs, shrubs, and subshrubs was conducted by Dr. Llewellyn Manske and Dr. Harold Goetz during the growing seasons of 1984 to 1985 with data collected biweekly. The study included 19 forbs, 1 shrub, and 3 subshrubs.

The study sites were located at the Dickinson Research Extension Center ranch near Manning, ND, and consisted of 720 acres of native rangeland pastures separated in three management treatments, each with two replications, and data collection sites established on sandy, shallow, and silty ecological sites. The ecological sites of the grazed treatments had matching paired plots, one grazed and the other with an ungrazed exclosure.

A long-term (30 year) change in prairie plant species abundance study was conducted by Dr. Llewellyn Manske during the growing seasons of 1983 to 2012 with data collected annually. The study included 1 upland sedge, 2 naturalized, 6 cool season and 8 warm season grasses, 44 forbs, and 4 shrubs and 5 subshrubs. The study sites were located at the Dickinson Research Extension Center ranch near Manning, ND, and consisted of 720 acres of native rangeland pastures separated into three management treatments, each with two replications, and data collection sites established on sandy, shallow, and silty ecological sites. The ecological sites of the grazed treatments had matching paired plots, one grazed and the other with an ungrazed exclosure.

Study Area

The physiography of the study area consists of the Unglaciated section of the Missouri Plateau (Fenneman 1931, 1946; Hunt 1974). Portions of this section were undoubtedly glaciated during glacial advances earlier than Wisconsin Age. However, there is little geologic evidence by older glaciation. The important distinction between the Unglaciated and Glaciated sections is the type and age of parent material from which the soil develops. The landscape surface of the Unglaciated section is highly eroded fluvial sedimentary deposits of material removed from the uplifted Rocky Mountains. Most of the deposition occurred from slow meandering streams during the Laramide Orogeny, that formed the mountains, and during the 20 to 30 million years of the late Cretaceous and early Tertiary Periods following the uplift. Intense widespread erosion of these sediments occurred from about 5 to 3 million years ago during the late Plicene Epoch (Bluemle 2000). The extensive erosion during this period removed about 500 to 1000 feet of sediments (Fenneman 1931). These fluvial Tertiary sediments had great differences in hardness and durability. The soft and unconsolidated material was easily removed and the harder coherent material had greater resistance to weathering and to erosional forces of wind and running water. Differential erosion formed a landscape with well developed integrated drainage systems of broad mature valleys and gently rolling uplands containing widely spaced large hills and buttes with erosion resistant caps raising 500 to 650 feet above the plain (Bluemle 2000).

Drainage of the Missouri Plateau during the highly erosional period of the Plicene (5 to 3 million years ago) was primarily north and northeast towards the Hudson Bay area. The climate became cooler about 2.6 million years ago and, about 700,000 years ago, the climate was cold enough to produce continental glaciers (Bluemle 2000). Early glacial advances blocked the northward paths of the rivers draining the Unglaciated section and diverted water flow into steeper southern routes. The increased gradient of several rivers caused drastic downcutting through areas of poorly consolidated, soft, fine textured sediments resulting in formation of badland regions (Fenneman 1931).

The soils of western North Dakota developed from eroded Tertiary fluvial sedimentary deposits in the Ustic-Frigid soil moisture-temperature regime. The soils in the Ustic soil moisture regime, typically of semi arid climates, are dry in some or all parts for 90 or more days in most years, but not dry in all parts for more than half the time, and are not dry for as long as 45 days during the 4 months that follow the summer solstice (21 June) in 6 or more years out of 10 years. The Frigid soil temperature regime has mean annual soil temperatures of less than 47° F (8° C) (Soil Survey Staff 1975). These soils are primarily Typic Borolls (semi arid cool Mollisols) and support vegetation of mid and short grasses of the Mixed Grass Prairie (Manske 2008b).

The geologic history of the Northern Plains was dynamic and the climate has changed several times. A major climate change resulted when the Rocky Mountains uplifted about 70 to 80 million years ago, forming a barrier that prevented humid Pacific Ocean air masses from flowing eastward. The Plains became much drier.

Two million years ago the climate became cooler and more humid, with several periods of glaciation. The periods of glacial advance were cool and humid, the interglacial periods warmer and drier. The changes in climate since the last glaciation period have strongly influenced the present conditions of the region. The last ice sheet reached its maximum advance between 14,000 and 12,000 years ago. About 10,000 years ago, a sudden change in the climate to drier and warmer summers but colder winters occurred. This major change accelerated the melting of the glacial ice. A spruce-aspen forest developed in the cool, moist conditions at the ice margin; this community graded into a deciduous forest, which graded into a grassland south of the Northern Plains. The climate became much drier and warmer between 10,000 and 5,000 years ago. During 8,500 and 4,500 years ago, the vegetation was a sagebrush and short grass community similar to vegetation in parts of Wyoming, and the region experienced frequent summer droughts and extensive soil erosion from wind (Bluemle 1977, 1991).

The climate changed about 5,000 years ago to conditions like those of the present, with cycles of wet and dry periods (Bluemle 1977, 1991; Manske 1994). The wet periods have been cool and humid, with greater amounts of precipitation. During the wet peiods, the vegetation increased in taller grasses and deciduous woodlands. The dry periods have been warmer, with reduced precipitation and recurrent summer droughts. During the dry periods, the vegetation decreased in woodlands and increased in grasslands, with the plant composition shifting from taller grass species to shorter grass species.

The current "native" plant species in the Northern Plains did not originate here. All of the plant species have migrated into the region by different mechanisms and at different times and rates. The present plant species have flora affinities to northern, eastern, western, Rocky Mountain, and Great Basin plant communities (Zaczkowski 1972). This wide mix of plant species in the Northern Plains formed from remnants of plant communities that reached periods of greater development during the wet and dry cycles when conditions favored these various plant community types. The large diversity of plant species that make up the mixed grass prairie permits dynamic responses to changes in climatic conditions by increasing the combination of plant species favored by any set of conditions (Manske 2008a).

Climatic conditions regulate growth and development of prairie plants. Length of daylight, temperature, precipitation, and water deficiency are the most important climatic factors that affect rangeland plants (Manske 2011b).

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. Water vapor is the most common greenhouse gas.

Day length period (photoperiod) is one of the most dependable cues by which plants time their activities in temperate zones. Day length 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, Daubenmine 1974, Barbour et al. 1987).

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 32° F (0° C) and 122° F (50° 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 32° F if plants are "hardened". High temperatures limit biological reactions because the complex structures of proteins are disrupted or denatured.

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, is an integral part of all living systems and 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 up to 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, 1995).

A water deficiency exists when the amount of rainfall received is less than potential evapotranspiration demand. 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. 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 (Manske 2016).

A technique reported by Emberger et al. (1963) was used to develop water deficiency months data from historical temperature and precipitation data (Manske 1998, 2013). 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) (Manske 2016).

Long-Term Weather-Dickinson

The NDSU Dickinson Research Extension Center campus is located in Dickinson, Stark county, western North Dakota, USA, at latitude 46° 53' N, longitude 102° 49' W, elevation 2,500 feet. The 118 year long-term (1892-2009) mean annual temperature was 40.9° F (4.9° C). January was the coldest month, with a mean temperature of 11.5° F (-11.4° C). July and August were the warmest months, with mean temperatures of 68.8° F (20.4° C) and 67.0° F (19.4° C), respectively. 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 (0° C). 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 118 year long-term mean annual precipitation was 16.0 inches (406.4 mm). The growing season precipitation (April to October) was 13.5 inches (342.9 mm), 84.5% of the annual precipitation. The early portion of the growing season (April to July) received 9.5 inches (241.3 mm), 59.5% of the annual precipitation and the latter portion of the growing season (August to October) received 4.0 inches (101.6 mm), 25.0% of the annual precipitation. Total precipitation received during the nongrowing season (November through March) was only 2.5 inches (63.5 mm), 15.6% of the annual precipitation (Manske et al. 2010).

Water stress develops in perennial plants during water deficiency periods when the amount of rainfall is less than evapotranspiration demand. Water deficiency months were identified from historical temperature and precipitation data by the ombrothermic diagram technique (Emberger et al. 1963). The long-term (1892-2009) ombrothermic diagram (figure 1) shows near water deficiency conditions during August, September, and October, and favorable water relations during April, May, June, and July (Manske 2010). Reoccurrence of water deficiency conditions during April, May, June, and July was 16.9%, 13.6%, 10.2%, and 38.1%, respectively, and during August, September, and October water deficiency reoccurred 52.5%, 50.0%, and 46.6% of the years, respectively. Long-term occurrence of water deficiency conditions was 32.7% of the growing season months, for a mean of 2.0 water deficient months per growing season (Manske et al. 2010).

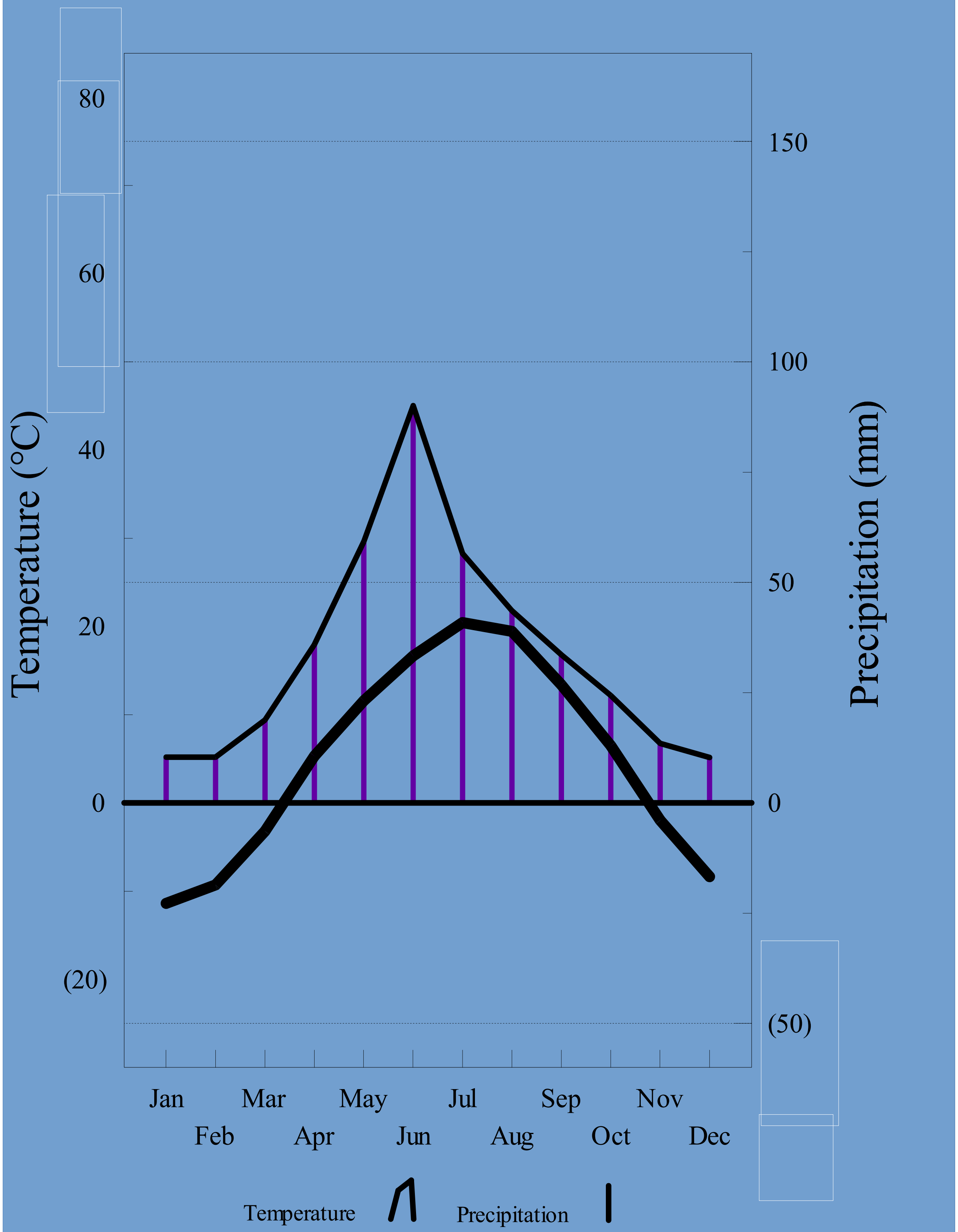

Fig. 1. Ombrothermic diagram of long-term (1892-2009) mean monthly temperature and monthly precipitation at Dickinson, North Dakota.

Growing Season Precipitation-Dickinson

The 1946-1947 Study

The growing season precipitation during 1940 to 1949 was 15.10 inches (111.88% of LTM). The growing season precipitation during 1940-1944 was 18.42 inches (136.52% of LTM). The growing season precipitation during 1945-1949 was 11.78 inches (87.32% of LTM). The last 5 years of the 1940's decade received 24.6% less precipitation than the first 5 years. Growing season precipitation of 1946 was 11.80 inches (87.47% of LTM). April through July precipitation was 81.95% of LTM and August through October precipitation was 100.76% of LTM. Growing season precipitation of 1947 was 16.93 inches (125.50% of LTM). April through July precipitation was 137.04% of LTM and August through October precipitation was 97.73% of LTM (table 1). Mean growing season precipitation of 1946-1947 was 14.37 inches (106.49% of LTM). The 1946 and 1947 growing seasons experienced 3.5 and 2.5 months of water deficiency conditions, respectively.

The 1955-1962 Study

Mean growing season precipitation of 1955-1962 was 12.81 inches (94.96% of LTM) with 38.5% of the months in water deficiency. Two growing seasons, 1958 and 1960, received precipitation at less than 75% of LTM. One growing season, 1957, received precipitation at greater than 125% of LTM. One growing season, 1962, received precipitation at greater than 100% of LTM (table 2). Six growing seasons, 1955, 1956, 1958, 1959, 1960, and 1961, had 2.5 or greater months in water deficiency. Two growing seasons, 1957 and 1962, had 1.5 or less months in water deficiency (table 3). During this 8 year study July, August, September, and October experienced water deficiency during four or five years (table 3).

The 1969-1971 Study

The mean monthly temperature and monthly precipitation for the perennial plant growing season months from four weather stations, Bowman, Marmarth, Medora, and Trotters, of southwestern North Dakota for 1969 to 1971 were reported by Zaczkowski (1972) and summarized for this report. July and August were the warmest months, with mean temperatures of 68.2° F and 72.4° F, respectively. Mean growing season precipitation of 1969-1971 was 14.24 inches (105.56% of LTM). The growing season of 1970 had the greatest precipitation at 16.49 inches (122.24% of LTM). The growing season of 1969 had the lowest precipitation at 11.80 inches (87.47% of LTM) (table 4). During this 3 year study, August experienced 3 years of water deficiency.

Table 1. Precipitation in inches and percent of long-term mean for perennial plant growing season months, Dickinson, ND, 1946-1947.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean									
1892-1997	1.44	2.31	3.54	2.24	1.75	1.30	0.91	13.49	15.95
1946	1.09	2.42	2.68	1.62	0.82	0.96	2.21	11.80	14.50
% of LTM	75.69	104.76	75.71	72.32	46.86	73.85	242.86	87.47	90.91
1947	1.70	0.73	8.48	2.15	2.58	0.68	0.61	16.93	18.86
% of LTM	118.06	31.60	239.55	95.98	147.43	52.31	67.03	125.50	118.24
1946-1947	1.40	1.58	5.58	1.89	1.70	0.82	1.41	14.37	16.68
% of LTM	96.88	68.18	157.63	84.15	97.14	63.08	154.95	106.49	104.58

Table 2. Precipitation in inches and percent of long-term mean for perennial plant growing season months, Dickinson, ND, 1955-1962.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1892-1997	1.44	2.31	3.54	2.24	1.75	1.30	0.91	13.49	15.95
1955	1.91	2.45	4.70	1.08	0.81	1.53	0.18	12.66	14.65
% of LTM	132.64	106.06	132.77	48.21	46.29	117.69	19.78	93.85	91.85
1956	0.22	2.90	1.17	3.01	2.55	0.76	0.43	11.04	12.70
% of LTM	15.28	125.54	33.05	134.38	145.71	58.46	47.25	81.84	79.62
1957	2.59	2.10	6.61	3.46	1.49	1.98	1.94	20.17	22.15
% of LTM	179.86	90.91	186.72	154.46	85.14	152.31	213.19	149.52	138.87
1958	0.57	0.45	3.26	3.86	0.57	0.06	0.65	9.42	12.18
% of LTM	39.58	19.48	92.09	172.32	32.57	4.62	71.43	69.83	76.36
1959	0.16	1.94	3.08	0.97	0.54	4.54	0.33	11.56	13.45
% of LTM	11.11	83.98	87.01	43.30	30.86	349.23	36.26	85.69	84.33
1960	0.35	2.23	3.06	0.58	2.16	0.14	0.02	8.54	10.23
% of LTM	24.31	96.54	86.44	25.89	123.43	10.77	2.20	63.31	61.14
1961	1.89	1.44	2.82	1.66	1.68	3.05	0.11	12.65	13.90
% of LTM	131.25	62.34	79.66	74.11	96.00	234.62	12.09	93.77	87.15
1962	1.12	6.18	2.07	3.22	2.52	0.75	0.55	16.41	18.34
% of LTM	77.78	267.53	58.47	143.75	144.00	57.69	60.44	121.65	114.98
1955-1962	1.10	2.46	3.35	2.23	1.55	1.60	0.53	12.81	14.70
% of LTM	76.39	106.49	94.63	99.55	88.57	123.08	58.24	94.96	92.16

Table 3. Growing season months with water deficiency conditions that caused water stress in perennial plants, Dickinson, ND, 1955-1962.

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
1955								2.5	41.7
1956								2.5	41.7
1957								1.0	16.7
1958								3.0	50.0
1959								2.5	41.7
1960								3.0	50.0
1961								2.5	41.7
1962								1.5	25.0
#	**2**	**1**	**1**	**4**	**5**	**4**	**5**	**18.5**	**38.5**
%	**25.0**	**12.5**	**12.5**	**50.0**	**62.5**	**50.0**	**62.5**		

Table 4. Three year mean monthly temperature and mean monthly precipitation for perennial plant growing season months from four weather stations, Bowman, Marmarth, Medora, and Trotters, of southwestern North Dakota, 1969 to 1971.								
	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season
Mean Temperature 1969-1971 °F	43.90	54.20	62.60	68.20	72.40	58.10	41.30	57.20
Mean Precipitation								
1969	1.27	1.41	5.08	2.71	0.41	0.18	0.74	11.80
1970	2.61	4.72	3.49	1.94	1.22	1.85	0.66	16.49
1971	1.93	1.27	6.45	0.48	0.10	3.47	0.70	14.40
1969-1971	1.94	2.47	5.01	1.71	0.58	1.83	0.70	14.24

Data from Zaczkowski 1972.

Long-Term Weather-DREC ranch

The NDSU Dickinson Research Extension Center ranch is located in Dunn county in western North Dakota, at 47° 14' north latitude, 102° 50' west longitude. Mean annual temperature is 42.3° F (5.7° C). January is the coldest month, with mean temperature of 14.6° F (-9.7° C). July and August are the warmest months, with mean temperatures of 69.7° F (20.9° C) and 68.6° F (20.3° C), respectively. Long-term (1982-2012) mean annual precipitation is 16.91 inches (429.61 mm). The perennial plant growing season precipitation (April to October) is 14.13 inches (358.97 mm) and is 83.6% of annual precipitation. June has the greatest monthly precipitation, at 3.27 inches (83.08 mm). The precipitation received during the 3-month period of May, June, and July (8.26 inches, 209.80 mm) accounts for 48.8% of the annual precipitation (Manske 2013).

Water deficiency months were identified from historical temperature and precipitation data by the ombrothermic diagram technique (Emberger et al. 1963). The long-term (1982-2012) ombrothermic diagram (figure 2) shows near water deficiency conditions during August and September when water deficiency reoccurred 54.8% and 58.1% of the years and shows favorable water relations during April, May, June, July, and October with reoccurrence of water deficiency conditions at 16.1%, 9.7%, 9.7%, 35.5%, and 35.5% of the years, respectively. Long-term occurrence of water deficiency conditions was 32.3% of the growing season months, for a mean of 2.0 water deficient months per growing season (Manske 2013).

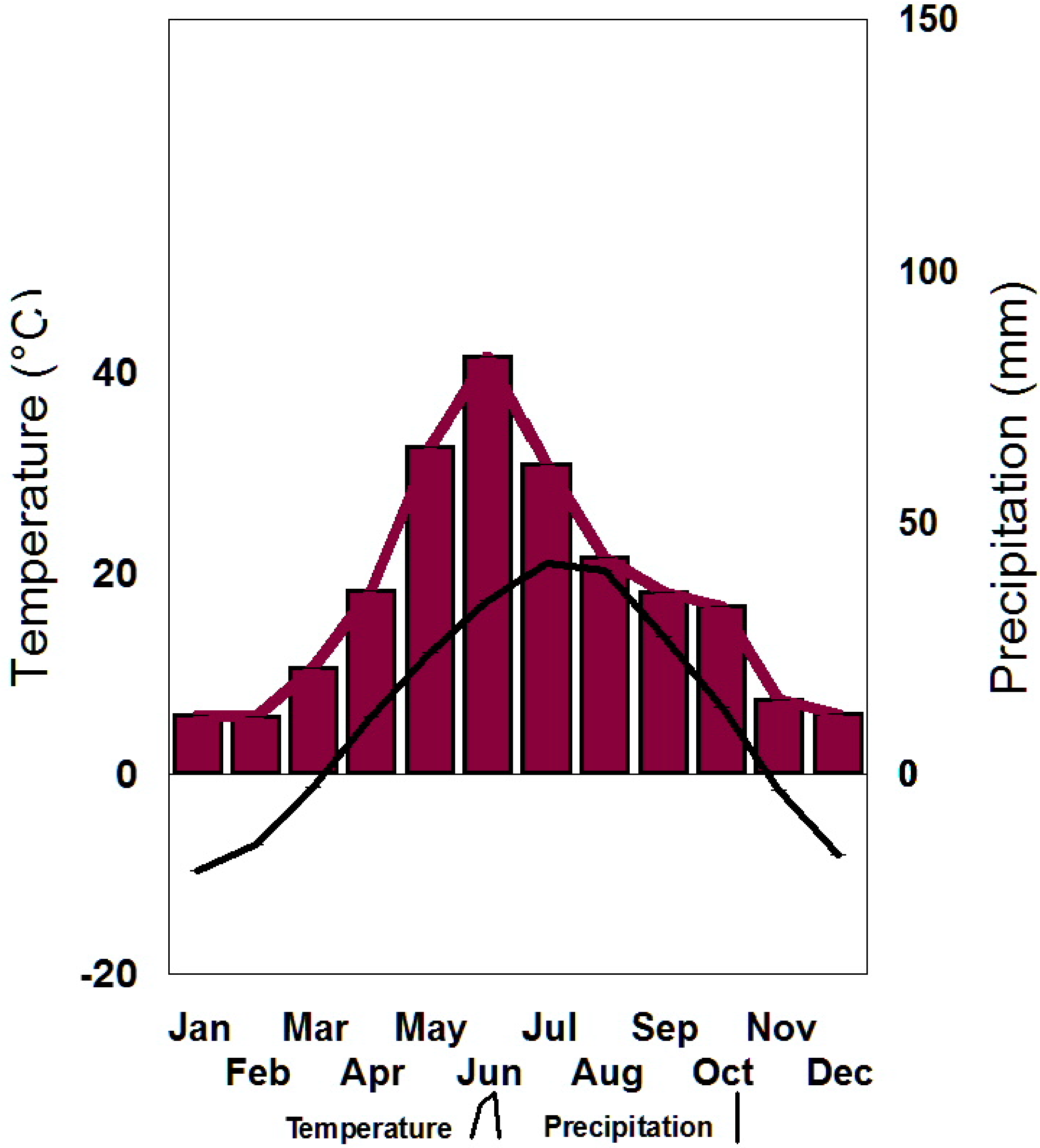

Figure 2. Ombrothermic diagram of long-term mean monthly temperature and monthly precipitation at the DREC Ranch, western North Dakota, 1982-2012.

'Growing Season Precipitation-DREC ranch
1983-1987

Autecological studies on prairie plants extend from 1983 to 2012 on the DREC ranch. The growing season precipitation information has been grouped into 5 and 6 year periods. Mean growing season precipitation of 1983-1987 was 13.59 inches (96.18% of LTM) with 33.3% of the months in water deficiency. None of the growing seasons received precipitation at less than 75% of LTM. One growing season, 1986, received precipitation at greater than 125% of LTM (table 5). Two growing seasons, 1984 and 1987, had greater than 2.0 months in water deficiency. Three growing seasons, 1983, 1985, and 1986, had less than 2.0 months in water deficiency (table 11).

Mean growing season precipitation during the forb, and shrub and subshrub autecology study period 1984-1985 was 12.25 inches (86.66% of LTM) with 33.3% of the months in water deficiency.

1988-1992

Mean growing season precipitation of 1988-1992 was low at 9.65 inches (68.29% of LTM) with 51.7% of the months in water deficiency. All of the growing seasons received precipitation at less than 90% of LTM. One growing season, 1988, received precipitation at less than 40% of LTM. One growing season, 1992, received precipitation at less than 75% of LTM (table 6). All of the growing seasons, 1988-1992, had 2.0 or greater months in water deficiency (table 11). The growing season of 1988 had 5.0 months in water deficiency which was the second greatest water deficiency since 1892. The growing seasons of 1936 had 5.5 months in water deficiency and 1934 had 4.5 months in water deficiency (Manske et al. 2010).

Mean growing season precipitation during the grass autecology study period of 1983-1989 was 11.98 inches (84.79% of LTM) with 42.8% of the months in water deficiency.

1993-1998

Mean growing season precipitation of 1993-1998 was 15.30 inches (108.28% of LTM) with 30.6% of the months in water deficiency. None of the growing seasons received precipitation at less than 75% of LTM. One growing season, 1998, received precipitation at greater than 125% of LTM. Three growing seasons, 1993, 1995, and 1997, received precipitation at greater than 100% of LTM (table 7). Three growing seasons, 1993, 1994, and 1995, had 2.0 or greater months in water deficiency. Three growing seasons, 1996, 1997, and 1998, had less than 2.0 months in water deficiency (table 11).

1999-2003

Mean growing season precipitation of 1999-2003 was 15.56 inches (110.12% of LTM) with 20.0% of the months in water deficiency. None of the growing seasons received precipitation at less than 75% of LTM. One growing season, 2002, received precipitation at greater than 125% of LTM. Three growing seasons, 1999, 2000, and 2001, received precipitation at greater than 100% of LTM (table 8). One growing season, 2001, had greater then 2.0 months in water deficiency. Four growing seasons, 1999, 2000, 2002, and 2003, had 1.0 or less months in water deficiency (table 11).

2004-2009

Mean growing season precipitation of 2004-2009 was 13.92 inches (98.51% of LTM) with 37.5% of the months in water deficiency. None of the growing seasons received precipitation at less than 75% of LTM and none at greater than 125% of LTM. Three growing seasons, 2005, 2006, and 2009, received precipitation at greater than 100% of LTM (table 9). Three growing seasons, 2005, 2007, and 2008, had 3.0 or greater months in water deficiency. One growing season, 2009, had 2.0 months in water deficiency. Two growing seasons, 2004 and 2006, had 1.0 month in water deficiency (table 11).

2010-2012

Mean growing season precipitation of 2010-2012 was 15.91 inches (112.60% of LTM) with 22.2% of the months in water deficiency. None of the growing seasons received precipitation at less than 75% of LTM. One growing season, 2011, received precipitation at greater than 125% of LTM. One growing season, 2010, received precipitation at greater than 100% of LTM (table 10). One growing season, 2012, had 2.0 months in water deficiency. Two growing seasons, 2010 and 2011, had less than 2.0 months in water deficiency (table 11).

1983-2012

Mean growing season precipitation during the long-term change in prairie species abundance study of 1983-2012 was 13.90 inches (98.38% of LTM) with 33.3% of the months in water deficiency. Two growing seasons (6.7%) received precipitation at less than 75% of LTM. Four growing seasons (13.3%) received precipitation at greater than 125% of LTM. Ten growing seasons (33.3%) received precipitation at greater than 100% of LTM. Sixteen growing seasons (53.3%) had 2.0 or greater months in water deficiency. Ten growing seasons (33.3%)

had 1.0 or less months in water deficiency. No growing seasons had zero months in water deficiency. Three growing seasons before and after this study, 1982, 2013, and 2015, had zero months in water deficiency (Manske 2016). During 1983-2012, water deficiency during August and September reoccurred at 56.7% and 60.0% of the years, respectively. Water deficiency during April, May, June, July and October reoccurred at 16.7%, 10.0%, 10.0%, 36.7%, and 36.7% of the years, respectively (table 12).

Table 5. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 1983-1987.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
1983	0.21	1.53	3.26	2.56	4.45	0.86	0.72	13.59	15.55
% of LTM	14.58	59.77	99.69	105.35	261.76	60.56	54.96	96.18	91.96
1984	2.87	0.00	5.30	0.11	1.92	0.53	0.96	11.69	12.88
% of LTM	199.31	0.00	162.08	4.53	112.94	37.32	73.28	82.73	76.17
1985	1.24	3.25	1.58	1.07	1.84	1.69	2.13	12.80	15.13
% of LTM	86.11	126.95	48.32	44.03	108.24	119.01	162.60	90.59	89.47
1986	3.13	3.68	2.58	3.04	0.46	5.29	0.18	18.36	22.96
% of LTM	217.36	143.75	78.90	125.10	27.06	372.54	13.74	129.94	135.78
1987	0.10	1.38	1.15	5.39	2.65	0.78	0.08	11.53	14.13
% of LTM	6.94	53.91	35.17	221.81	155.88	54.93	6.11	81.60	83.56
1983-1987	1.51	1.97	2.77	2.43	2.26	1.83	0.81	13.59	16.13
% of LTM	104.86	76.95	84.71	100.00	132.94	128.87	61.83	96.18	95.39

Table 6. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 1988-1992.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
1988	0.00	1.85	1.70	0.88	0.03	0.73	0.11	5.30	9.03
% of LTM	0.00	72.27	51.99	36.21	1.76	51.41	8.40	37.51	53.40
1989	2.92	1.73	1.63	1.30	1.36	0.70	0.96	10.60	13.07
% of LTM	202.78	67.58	49.85	53.50	80.00	49.30	73.28	75.02	77.29
1990	2.03	2.39	3.75	1.13	0.31	0.68	0.85	11.14	11.97
% of LTM	140.97	93.36	114.68	46.50	18.24	47.89	64.89	78.84	70.79
1991	1.97	1.16	3.95	1.43	0.55	2.17	1.31	12.54	13.30
% of LTM	136.81	45.31	120.80	58.85	32.35	152.82	100.00	88.75	78.65
1992	0.81	0.68	1.59	2.70	2.02	0.72	0.16	8.68	11.23
% of LTM	56.25	26.56	48.62	111.11	118.82	50.70	12.21	61.43	66.41
1988-1992	1.55	1.56	2.52	1.49	0.85	1.00	0.68	9.65	11.72
% of LTM	107.64	60.94	77.06	61.32	50.00	70.42	51.91	68.29	69.31

Table 7. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 1993-1998.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
1993	1.41	1.71	4.57	5.10	1.24	0.18	0.05	14.26	17.36
% of LTM	97.92	66.80	139.76	209.88	72.94	12.68	3.82	100.92	102.66
1994	0.86	1.46	4.51	1.07	0.31	1.08	4.58	13.87	16.14
% of LTM	59.72	57.03	137.92	44.03	18.24	76.06	349.62	98.16	95.45
1995	1.01	4.32	0.68	4.62	3.16	0.00	0.67	14.46	16.24
% of LTM	70.14	168.75	20.80	190.12	185.88	0.00	51.15	102.34	96.04
1996	0.14	3.07	1.86	2.55	1.72	2.51	0.09	11.94	15.97
% of LTM	9.72	119.92	56.88	104.94	101.18	176.76	6.87	84.50	94.44
1997	2.89	0.95	5.02	5.41	0.76	1.75	0.78	17.56	18.61
% of LTM	200.69	37.11	153.52	222.63	44.71	123.24	59.54	124.27	110.05
1998	0.40	1.51	5.98	2.11	4.60	0.71	4.38	19.69	22.42
% of LTM	27.78	58.98	182.87	86.83	270.59	50.00	334.35	139.35	132.58
1993-1998	1.12	2.17	3.77	3.48	1.97	1.04	1.76	15.30	17.79
% of LTM	77.78	84.77	115.29	143.21	115.88	73.24	134.35	108.28	105.20

Table 8. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 1999-2003.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
1999	1.10	4.93	1.59	1.80	2.70	2.40	0.00	14.52	15.56
% of LTM	76.39	192.58	48.62	74.07	158.82	169.01	0.00	102.76	92.02
2000	1.26	1.90	3.77	2.77	2.74	1.09	1.46	14.99	20.23
% of LTM	87.50	74.22	115.29	113.99	161.18	76.76	111.45	106.09	119.63
2001	2.70	0.53	6.36	4.87	0.00	1.94	0.00	16.40	18.03
% of LTM	187.50	20.70	194.50	200.41	0.00	136.62	0.00	116.07	106.62
2002	1.14	2.18	5.40	4.27	4.24	0.74	0.88	18.85	21.88
% of LTM	79.17	85.16	165.14	175.72	249.41	52.11	67.18	133.40	129.39
2003	1.30	4.34	1.42	2.03	0.82	2.37	0.74	13.02	19.12
% of LTM	90.28	169.53	43.43	83.54	48.24	166.90	56.49	92.14	113.07
1999-2003	1.50	2.78	3.71	3.15	2.10	1.71	0.61	15.56	18.96
% of LTM	104.17	108.59	113.46	129.63	123.53	120.42	46.56	110.12	112.12

Table 9. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 2004-2009.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
2004	0.89	1.31	1.65	2.30	0.93	2.57	3.10	12.75	16.51
% of LTM	61.81	51.17	50.46	94.65	54.71	180.99	236.64	90.23	97.63
2005	0.96	6.01	6.05	0.60	1.52	0.50	1.96	17.60	21.51
% of LTM	66.67	234.77	185.02	24.69	89.41	35.21	149.62	124.56	127.20
2006	2.78	2.82	2.13	0.96	2.87	1.42	2.01	14.99	17.70
% of LTM	193.06	110.16	65.14	39.51	168.82	100.00	153.44	106.09	104.67
2007	1.58	4.64	1.80	1.05	0.78	0.76	0.26	10.87	13.94
% of LTM	109.72	181.25	55.05	43.21	45.88	53.52	19.85	76.93	82.44
2008	0.61	2.79	4.02	1.06	1.02	1.04	1.68	12.22	14.88
% of LTM	42.36	108.98	122.94	43.62	60.00	73.24	128.24	86.48	87.99
2009	1.49	2.47	3.84	3.24	0.95	1.15	1.95	15.09	17.89
% of LTM	103.47	96.48	117.43	133.33	55.88	80.99	148.86	106.79	105.80
2004-2009	1.39	3.34	3.25	1.54	1.35	1.24	1.83	13.92	17.07
% of LTM	96.53	130.47	99.39	63.37	79.41	87.32	139.69	98.51	100.95

Table 10. Precipitation in inches and percent of long-term mean for perennial plant growing season months, DREC ranch, 2010-2012.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2012	1.44	2.56	3.27	2.43	1.70	1.42	1.31	14.13	16.91
2010	1.43	3.70	3.50	1.94	1.39	4.09	0.13	16.18	19.03
% of LTM	99.31	144.53	107.03	79.84	81.76	288.03	9.92	114.51	112.54
2011	1.66	6.87	2.15	2.33	2.70	1.76	0.44	17.91	21.28
% of LTM	115.28	268.36	65.75	95.88	158.82	123.94	33.59	126.75	125.84
2012	2.38	1.58	4.31	1.98	0.82	0.21	2.35	13.63	15.46
% of LTM	165.28	61.72	131.80	81.48	48.24	14.79	179.39	96.46	91.43
2010-2012	1.82	4.05	3.32	2.08	1.64	2.02	0.97	15.91	18.59
% of LTM	126.39	158.20	101.53	85.60	96.47	142.25	74.05	112.60	109.93

Table 11. Growing season months with water deficiency conditions that caused water stress in perennial plants, DREC ranch, 1983-2012.

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
1983								1.5	25.0
1984								3.0	50.0
1985								1.0	16.7
1986								1.5	25.0
1987								3.0	50.0
#	**2**	**1**	**1**	**2**	**1**	**3**	**2**	**10.0**	**33.3**
%	**40.0**	**20.0**	**20.0**	**40.0**	**20.0**	**60.0**	**40.0**		
1988								5.0	83.3
1989								3.0	50.0
1990								3.0	50.0
1991								2.0	33.3
1992								2.5	41.7
#	**1**	**1**	**1**	**4**	**4**	**4**	**2**	**15.5**	**51.7**
%	**20.0**	**20.0**	**20.0**	**80.0**	**80.0**	**80.0**	**40.0**		
1993								2.5	41.7
1994								3.0	50.0
1995								2.0	33.3
1996								1.0	16.7
1997								1.0	16.7
1998								1.5	25.0
#	**2**	**0**	**1**	**1**	**3**	**4**	**2**	**11.0**	**30.6**
%	**33.3**	**0.0**	**16.7**	**16.7**	**50.0**	**66.7**	**33.3**		

Table 11 (cont.). Growing season months with water deficiency conditions that caused water stress in perennial plants, DREC ranch, 1983-2012.

	APR	MAY	JUN	JUL	AUG	SEP	OCT	# Months	% 6 Months 15 Apr-15 Oct
1999								0.5	8.3
2000								1.0	16.7
2001								2.5	41.7
2002								1.0	16.7
2003								1.0	16.7
#	**0**	**1**	**0**	**0**	**2**	**2**	**2**	**6.0**	**20.0**
%	**0.0**	**20.0**	**0.0**	**0.0**	**40.0**	**40.0**	**40.0**		
2004								1.0	16.7
2005								3.0	50.0
2006								1.0	16.7
2007								3.5	58.3
2008								3.0	50.0
2009								2.0	33.3
#	**0**	**0**	**0**	**4**	**5**	**4**	**1**	**13.5**	**37.5**
%	**0.0**	**0.0**	**0.0**	**66.7**	**83.3**	**66.7**	**16.7**		
2010								1.5	25.0
2011								0.5	8.3
2012								2.0	33.3
#	**0**	**0**	**0**	**0**	**2**	**1**	**2**	**4.0**	**22.2**
%	**0.0**	**0.0**	**0.0**	**0.0**	**66.7**	**33.3**	**66.7**		

Table 12. Growing season months with water deficiency, DREC ranch, 1983-2012.

	Apr	May	Jun	Jul	Aug	Sep	Oct	# Months	% 6 Months 15 Apr-15 Oct
Total	5	3	3	11	17	18	11	60.0	33.3
% of 30 Years	16.7	10.0	10.0	36.7	56.7	60.0	36.7		

Treatments at the DREC ranch

The native rangeland study sites were on the Dickinson Research Extension Center (DREC) ranch, operated by North Dakota State University (NDSU), and located in Dunn County, 20 miles north of Dickinson, in western North Dakota, USA. Effects from three management treatments were evaluated 1) long-term nongrazed control, 2) 4.5-month seasonlong, and 3) 4.5-month twice-over rotation system. Each management treatment was replicated two times.

The long-term nongrazed control management treatment was designed with large exclosures that contained vegetation that had not been defoliated by grazing, mowing, or burning.

The 4.5-month seasonlong grazing system was the traditional management treatment. A single pasture was grazed for 137 days from early June to mid October stocked at 2.86 acres per cow-calf pair per month.

The 4.5-month twice-over rotation grazing system was the biologically effective treatment with the partial defoliation periods coordinated with the grass phenological growth stages. A set of three pastures were grazed for a total of 137 days from early June to mid October stocked at 2.20 acres per cow-calf pair per month. Each pasture was grazed for two periods, one 15-day period between 1 June and 15 July (when lead tillers of grasses were between the 3.5 new leaf stage and flowering stage) and one 30-day period between 15 July (after secondary tillers of grasses reached the 3.5 new leaf stage) and mid October. The first pasture grazed in the sequence was the last pasture grazed the previous year. First year, A, B, C; second year C, A, B; third year B, C, A; and then repeat first year.

The effects from each of the three management treatments were evaluated on sandy, shallow, and silty ecological sites. Permanent sample plots were established within the long-term nongrazed exclosures. On the two grazed treatments, permanent sample plots were organized in a paired plot design with one plot grazed and the other plot ungrazed that was protected by a 16' X 32' (4.88 m X 9.75 m) stock panal exclosure to prevent access by livestock.

Soil Biological Activity

The below ground biological activities were extremely dissimilar for the three management treatments causing differential effects on the individual prairie plant species.

Rhizosphere volume associated with perennial grass roots was determined from two replicated intact soil cores from silty ecological sites collected monthly during 2002. The volume of each rhizosphere around every grass root was determined by measuring the length and diameter with a vernier caliper. The rhizosphere volume on the three management treatments were not different during June. During August and September, the rhizosphere volumes were not different on the nongrazed and seasonlong treatments at 2415.22 cm^3/m^3 and 1883.00 cm^3/m^3, respectively, however, the rhizosphere volume had been significantly increased at 6884.67 cm^3/m^3 on the twice-over rotation treatment by the stimulation during the first grazing period (figure 3).

The greater volume of rhizosphere on the twice-over treatment resulted in a greater biomass of bacteria, protozoa, endomycorrhizal fungi, and ectomycorrhizal fungi (Manske 2011a). These two types of soil fungi secrete great quantities of adhesive polysaccharides that bond soil particles into aggregates resulting in increased soil pore spaces, increased rooting depth, and increased water holding capacity.

The twice-over rotation treatment had greater quantities of infiltrated soil water than the seasonlong and nongrazed treatments. Soil water was determined monthly by the gravimetric procedure. Mean growing season infiltrated soil water (0-48 inches) on the twice-over treatment (2013-2014) was 2.72 inches (44.0%) greater and significantly different than that on the nongrazed treatment and was 1.38 inches (18.4%) greater and not significantly different than that on the seasonlong treatment. Mean growing season soil water (0-48 inches) on the seasonlong treatment was 1.34 inches (21.7%) greater and not significantly different than that on the nongrazed treatment (table 13).

Production of herbage and livestock biomass at biological potential levels on prairie ecosystems depends on the availability of essential elements at the required quantities. The major essential elements are carbon, hydrogen, nitrogen, and oxygen and the minor essential elements are the macronutrients and micronutrients. Productivity of prairie ecosystems degrades (decrease) when output of essential elements is greater than input and productivity aggrades (increase) when input of essential elements is greater than output (Manske 2012).

Soil organic matter is the primary nutrient reservoir of prairie ecosystems and contains the major essential elements and most of the minor essential elements (Brady 1974, Van Veen and Paul 1981, Burke et al. 1989). An increase or decrease in the quantity of soil organic matter is a direct indication of soil primary productivity and is a sensitive measure of changes in soil quality and ecosystem functionality (Burke et al. 1989, Gregorich et al. 1994).

Percent soil organic matter was determined by analysis of treatment silty soil (2013-2014). Weight of soil organic matter (SOM), soil organic carbon (SOC), and soil organic nitrogen (SON) were determined from the weight of silty soil at incremental depths and the percent organic matter, the percent organic carbon, and the percent organic nitrogen, respectively. The quantities of soil organic parameters on silty ecological sites should have been the same on all three management treatments at the start of these studies in 1983. Differences in the organic quantities on the treatments after 32 years would be caused by the effects on the soil microorganism biomass and the ecosystem biogeochemical processes and the resulting affects on soil quality and ecosystems productivity.

Soil organic matter (SOM) accumulation on the twice-over treatment was 117.0% greater than that on the nongrazed treatment and was 54.1% greater than that on the seasonlong treatment. Soil organic matter (SOM) accumulation on the seasonlong treatment was 91.1% greater than that on the nongrazed treatment (table 14, figure 4).

The twice-over treatment had accumulated 2.3 tons/ac/yr of soil organic carbon (SOC) in 32 years more than the annual amount that accumulated on the nongrazed treatment and accumulated 0.5 tons/ac/yr of SOC more than the annual amount on the seasonlong treatment. The annual accumulation of SOC on the seasonlong treatment was 1.8 tons/ac/yr more than the annual accumulation on the nongrazed treatment (table 14, figure 5).

The annual quantity of soil organic nitrogen (SON) accumulation on the twice-over treatment in 32 years was 450.6 lbs/ac/yr more than the annual amount on the nongrazed treatment and was 99.5 lbs/ac/yr more than the annual amount on the seasonlong treatment. The annual accumualtion of SON on the seasonlong treatment was 351.1 lbs/ac/yr more than the annual amount on the nongrazed treatment (table 14, figure 6).

Soil organic nitrogen (SON) cannot be used by prairie plants. Organic nitrogen must be converted into mineral nitrogen by soil microorganisms. Greater quantities of organic nitrogen can be mineralized to available mineral nitrogen by a larger volume and greater biomass of rhizosphere microorganisms (Coleman et al. 1983, Schimel, Coleman, and Horton 1985). The quantity of available soil mineral nitrogen is the major limiting factor of herbage growth on prairie ecosystems (Wight and Black 1979). A minimum quantity of mineralization of soil organic matter that supplies 100 pounds of mineral nitrogen per acre is required to sustain herbage production at biological potential levels on prairie ecosystems of the Northern Plains (Wight and Black 1972).

The quantity of available soil mineral nitrogen (NO_3 nitrate and NH_4 ammonium) varies with changes in soil microorganism biomass and plant phenological growth and development during the growing season (Whitman 1975) and is the net difference between the total quantity of soil organic nitrogen (SON) mineralized by soil microorganisms and the quantity of mineral nitrogen immobilized (transformed) by plants and soil microbes (Brady 1974, Legg 1975).

The twice-over treatment was the only treatment that had a large enough rhizosphere volume and microorganism biomass to mineralize nitrogen at greater quantities than the minimum threshold amount of 100 lbs/ac to maintain ecosystem productivity at biological potential levels. The quantity of mineral nitrogen available to the 24 inch soil depth on the nongrazed and seasonlong treatments was 58.4 lbs/ac and 85.9 lbs/ac, respectively, which were 41.6% and 14.1% lower than the minimum quantity required (table 15, figure 7).

The 102.6 lbs/ac of soil mineral nitrogen available on the twice-over treatment was 75.7% and 19.4% greater than the quantities of mineral nitrogen available on the nongrazed and seasonlong treatments, respectively. The quantity of soil mineral nitrogen available on the seasonlong treatment was 47.1% greater than that on the nongrazed treatment (table 15, figure 7).

Greater quantities of soil mineral nitrogen transformed indicates greater prairie ecosystem productivity. The mean quantity of mineral nitrogen transformed monthly to organic nitrogen on the twice-over, seasonlong, and nongrazed treatments was 38.1 lbs/ac, 25.8 lbs/ac, and 10.1 lbs/ac, respectively. The quantity of transformed nitrogen on the twice-over treatment was 277.2% greater than that on the nongrazed treatment and was 48.0% greater than that on the seasonlong treatment. The quantity of transformed nitrogen on the seasonlong treatment was 155.4% greater than that on the nongrazed treatment (figure 7).

The twice-over rotation grazing management system is the biologically effective management strategy that is coordinated with grass phenological growth stage and meets the biological requirements of the perennial grass plants and rhizosphere organisms (Manske 1999, 2010b, 2011a). Healthy grass plants capture and fix carbon during photosynthesis and produce carbohydrates in quantities greater than the amount needed for tiller growth and development (Coyne et al. 1995). Partial defoliation of grass tillers that removes about 25% to 33% of the aboveground leaf material at vegetative phenological growth stages between the three and a half new leaf stage and the flower (anthesis) stage (Manske 2009, 2011a) by large grazing graminivores causes greater quantities of exudated material containing simple carbohydrates to be released from the grass tillers through the roots into the rhizosphere (Hamilton and Frank 2001). With the increase in availability of carbon compounds in the rhizosphere, the biomass and activity of the microorganisms increases (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). The increase in rhizosphere organism biomass and activity causes greater rates of mineralization of soil organic nitrogen (Coleman et al. 1983, Clarholm 1985, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002,Driver et al. 2005) that results in mineral nitrogen to be available at quantities greater than the threhold amount of 100 lbs/ac (table 15, figure 7).

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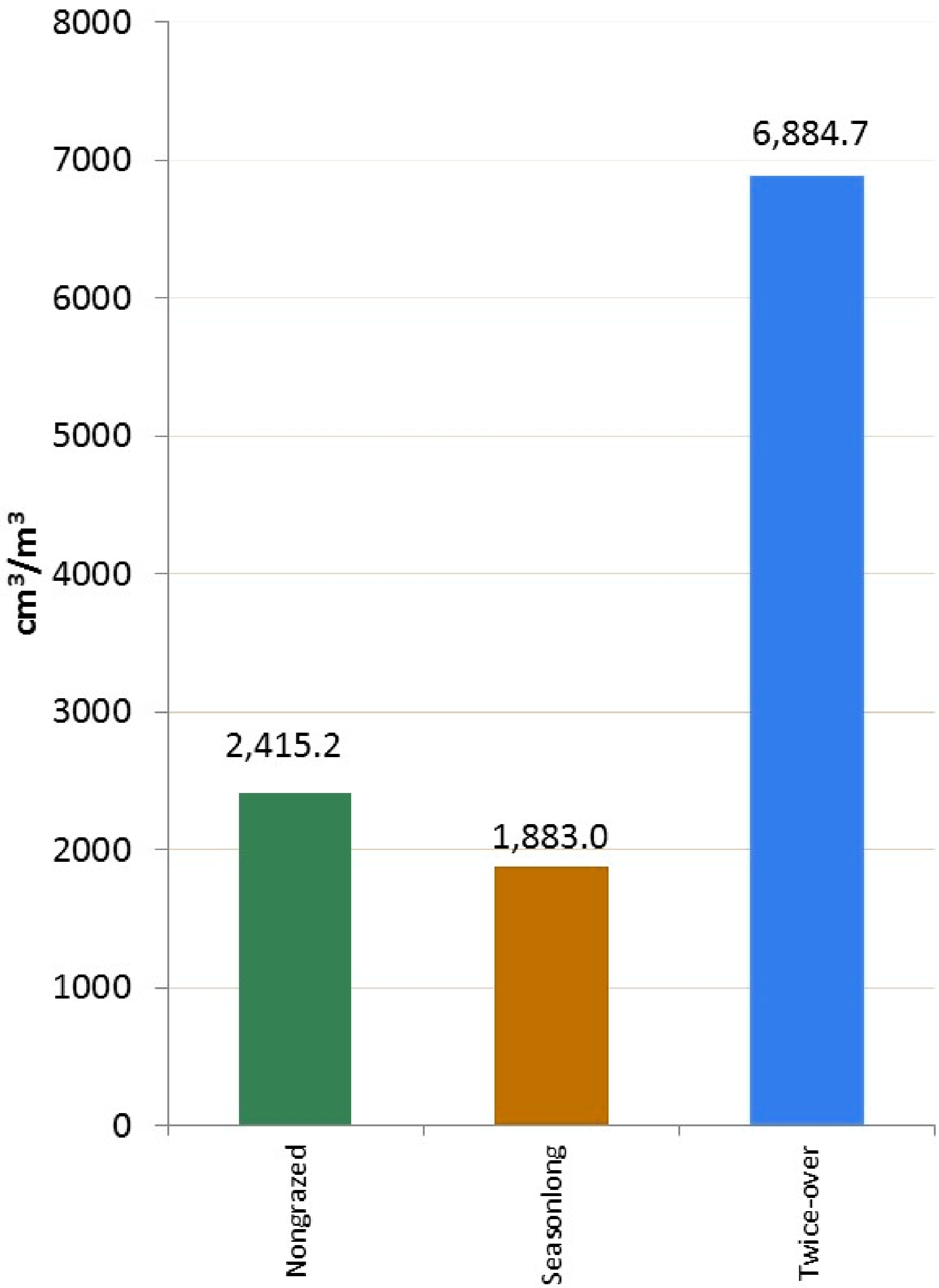

Figure 3. Rhizosphere Volume in cm^3/m^3 during August and September on Nongrazed, Seasonlong, and Twice-over rotation management strategies, 2002.

Table 13. Mean inches of soil water at incremental depths during the growing season on the silty ecological sites of the three grazing management treatments, 2013-2014.

	Growing Season Months						
Soil Depth (inches)	Apr	May	Jun	Jul	Aug	Sep	Oct
Nongrazed							
0-24	3.77	3.54	2.67	1.97	2.61	2.97	3.28
24-48	3.76	3.49	3.37	2.88	2.87	2.82	3.24
0-48	7.53	7.03	6.04	4.85	5.48	5.79	6.52
Seasonlong							
0-24	4.76	4.76	4.21	3.20	3.49	3.04	4.27
24-48	3.38	3.88	4.26	4.19	2.67	3.08	3.57
0-48	8.14	8.63	8.45	7.37	6.14	6.10	7.83
Twice-over							
0-24	5.75	5.15	4.87	3.67	4.59	4.41	5.36
24-48	2.91	4.28	5.10	4.17	3.92	4.00	4.15
0-48	8.66	9.43	9.95	7.83	8.52	8.39	9.49

Table 14. Soil organic matter (SOM), soil organic carbon (SOC), and soil organic nitrogen (SON) at incremental depths during June on silty ecological sites of the three grazing management treatments, 2013-2014.

	Soil Depths (Inches)					
	0-6	6-12	12-24	24-36	36-48	0-48
Nongrazed						
SOM						
%	3.08	1.89	1.45	1.15	0.98	1.47
tons/ac	24.03	16.67	25.64	20.81	19.60	106.74
SOC						
%	1.79	1.10	0.84	0.67	0.57	0.86
tons/ac	13.96	9.70	14.85	12.12	11.40	62.04
SON						
%	0.179	0.110	0.084	0.067	0.057	0.086
lbs/ac	2,792.74	1,940.07	2,970.81	2,424.26	2,279.53	12,407.41
Seasonlong						
SOM						
%	6.07	3.38	2.55	2.26	2.04	2.82
tons/ac	47.35	29.81	45.09	40.89	40.79	203.93
SOC						
%	3.52	1.96	1.48	1.31	1.18	1.63
tons/ac	27.46	17.28	26.17	23.70	23.60	118.21
SON						
%	0.352	0.196	0.148	0.131	0.118	0.163
lbs/ac	5,491.88	3,456.85	5,234.28	4,739.97	4,719.02	23,642.00
Twice-over						
SOM						
%	5.98	4.19	3.38	2.56	2.09	3.20
tons/ac	46.65	36.95	59.77	46.31	41.79	231.47
SOC						
%	3.47	2.43	1.96	1.48	1.21	1.85
tons/ac	27.07	21.43	34.66	26.78	24.19	134.13
SON						
%	0.347	0.243	0.196	0.148	0.121	0.185
lbs/ac	5,413.87	4,285.79	6,931.89	5,355.08	4,838.99	26,825.62

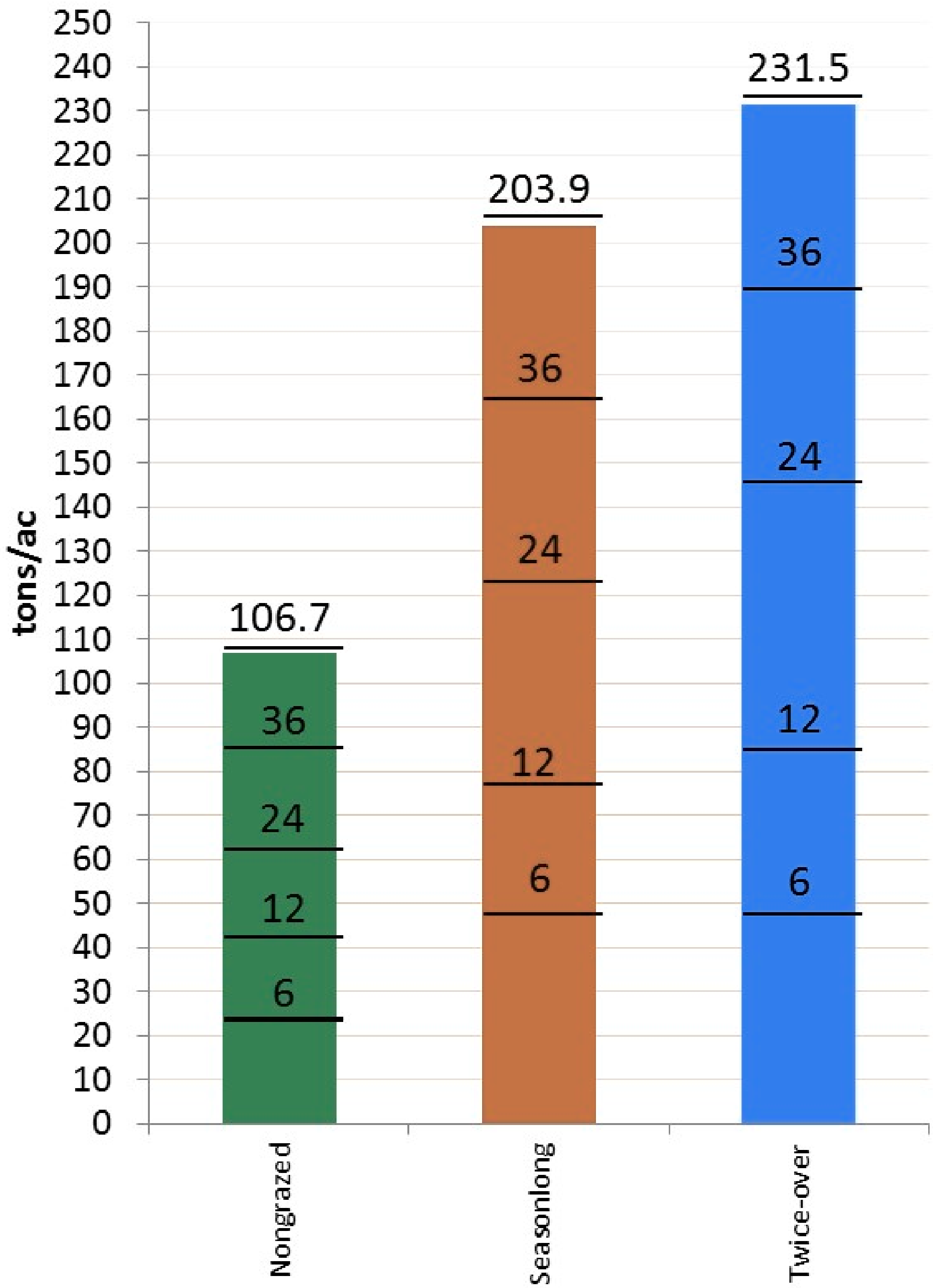

Figure 4. Soil Organic Matter (SOM) in tons/ac at 5 incremental depths to 48 inches on Nongrazed, Seasonlong, and Twice-over rotation management strategies after 32 years.

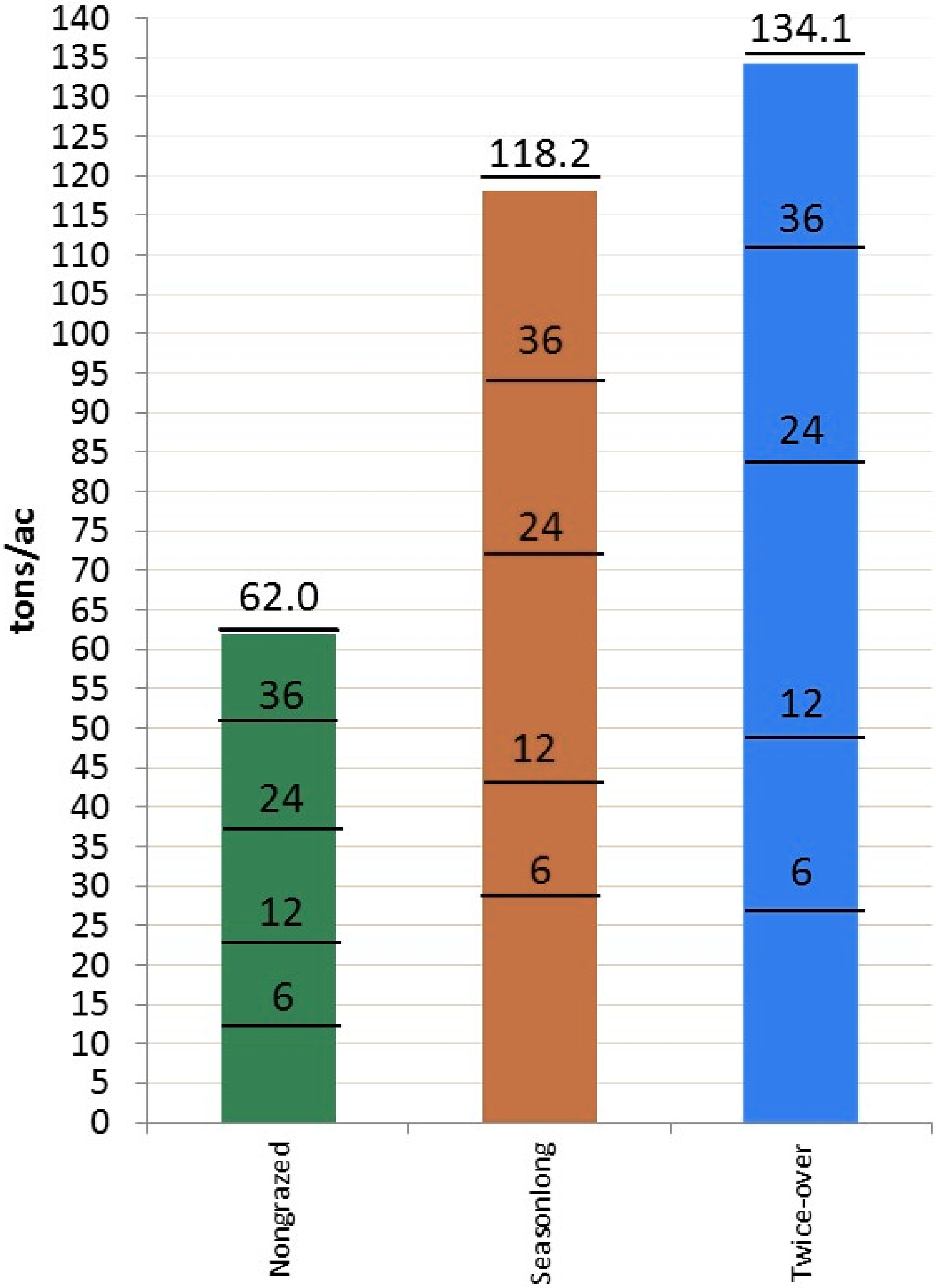

Figure 5. Soil Organic Carbon (SOC) in tons/ac at 5 incremental depths to 48 inches on Nongrazed, Seasonlong, and Twice-over rotation management strategies after 32 years.

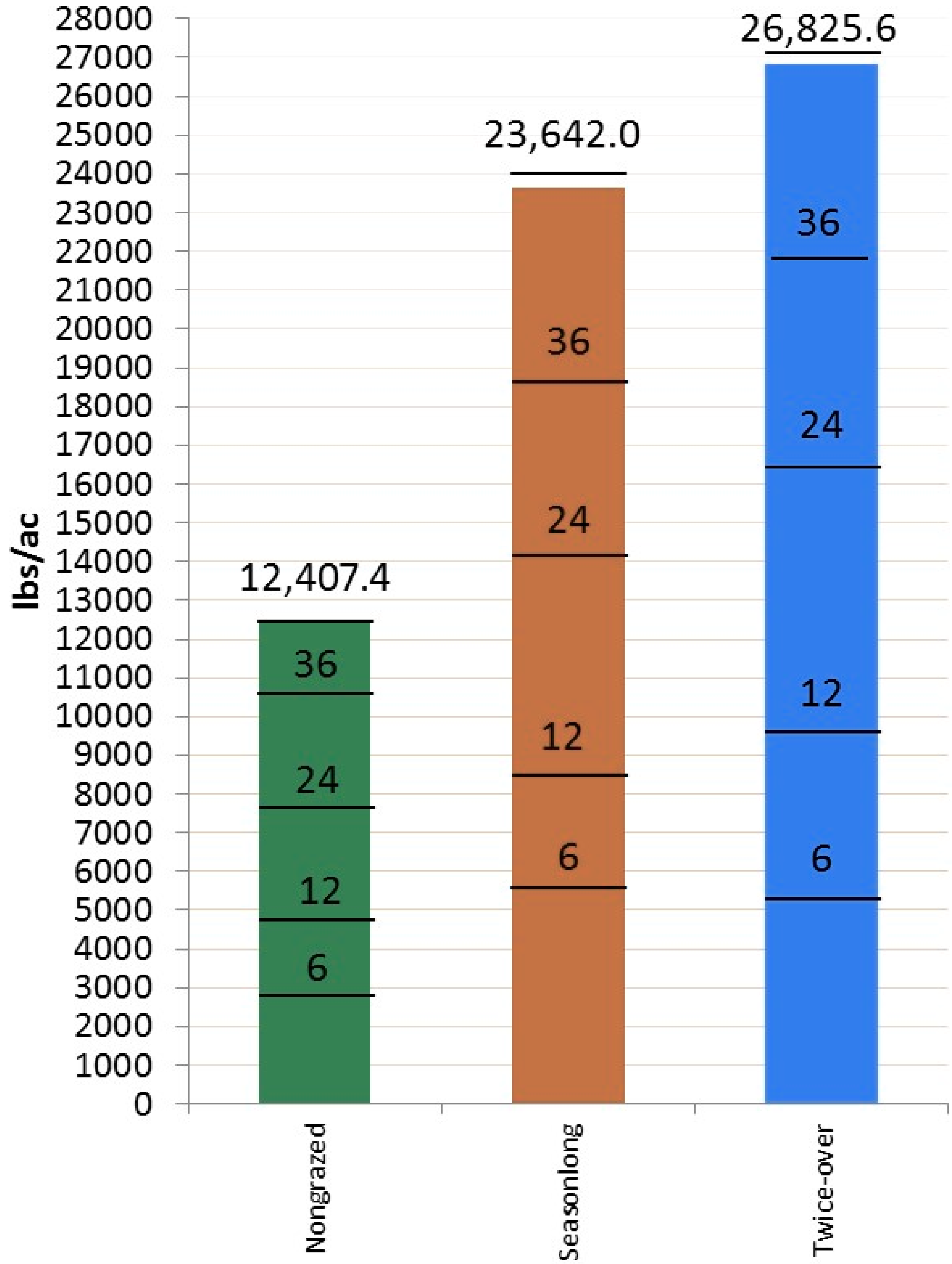

Figure 6. Soil Organic Nitrogen (SON) in lbs/ac at 5 incremental depths to 48 inches on Nongrazed, Seasonlong, and Twice-over rotation management strategies after 32 years.

Table 15. Available mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac at 0-24 inch soil depth during the growing season on silty ecological sites of the three grazing management treatments, 2013-2014.

	Growing Season Months					
Soil Depth 0-24 inches	May	Jun	Jul	Aug	Sep	Oct
Nongrazed						
NO_3 nitrate	16.25	10.26	6.25	7.88	12.25	8.88
NH_4 ammonium	42.15	38.52	39.89	34.11	39.49	43.89
$NO_3 + NH_4$	58.40	48.78	46.14	41.99	51.74	53.77
Seasonlong						
NO_3 nitrate	37.11	29.26	9.57	14.08	15.80	11.14
NH_4 ammonium	48.82	48.32	41.57	41.61	40.91	48.57
$NO_3 + NH_4$	85.92	77.57	51.13	55.68	56.71	59.70
Twice-over						
NO_3 nitrate	43.37	29.07	6.51	11.57	14.82	9.38
NH_4 ammonium	59.21	57.23	43.88	48.37	46.51	54.89
$NO_3 + NH_4$	102.57	86.29	50.38	59.93	61.33	64.27

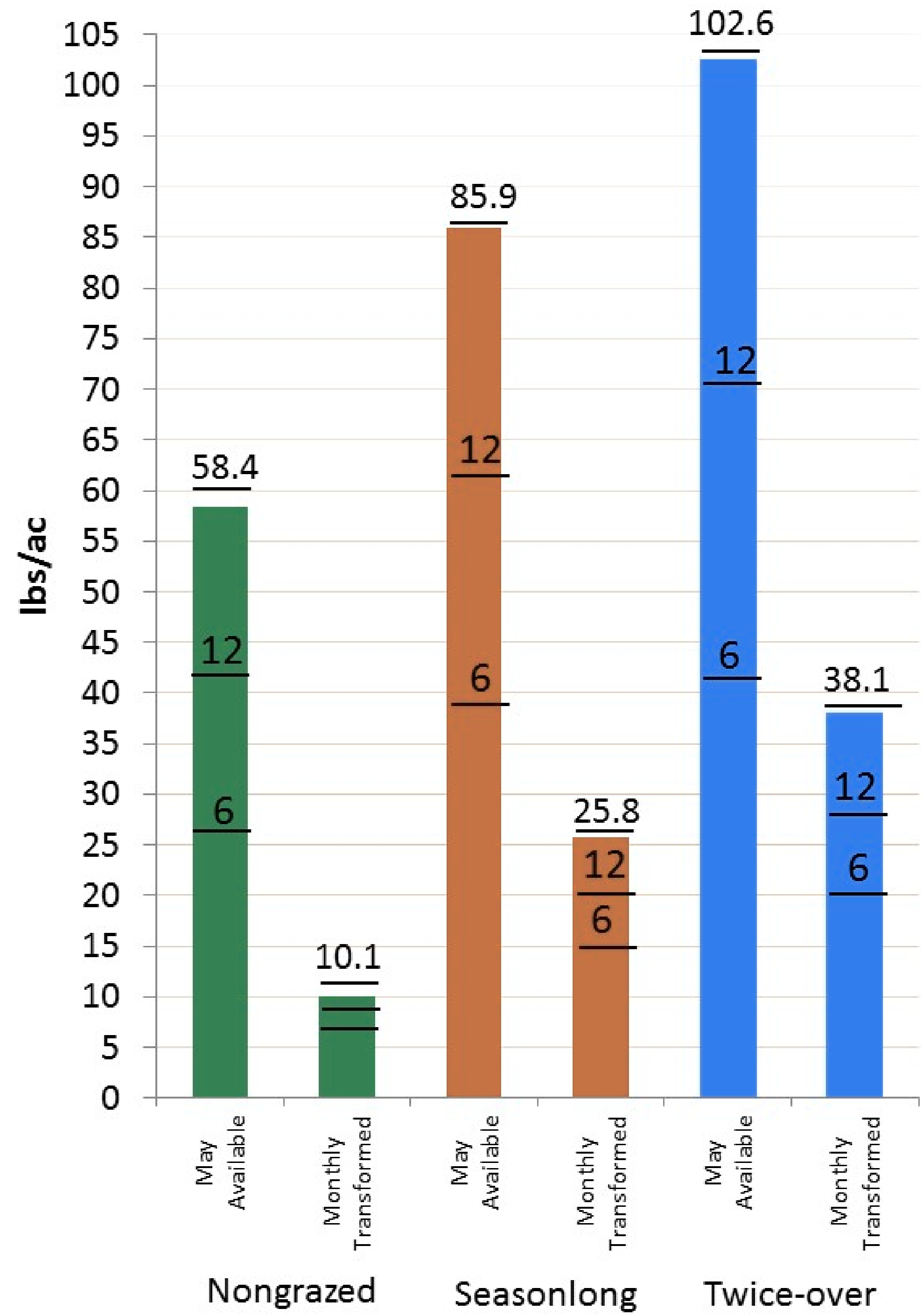

Figure 7. Mineral Nitrogen ($NO_3 + NH_4$) monthly available and transformed in lbs/ac at 3 incremental depths to 24 inches on Nongrazed, Seasonlong, and Twice-over rotation management strategies, 2013-2014.

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