

EFFECTS FROM LONG-TERM NONGRAZING SINCE 1936



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Does removal of cattle grazing promote development of stable climax plant communities and preserve prairie grasslands in perpetuity?

When the nonagricultural public observe deteriorated areas of public rangeland, they assume that cattle grazing, not poor management, is the cause for the damage to these areas of rangeland.

Degradation of rangelands is caused by poor management of cattle grazing, not simply any cattle grazing. What would be the consequences to grassland ecosystems if cattle grazing were successfully removed from public rangelands.

A long-term project for studying the effects from nongrazing of rangelands compared to the effects from seasonlong grazing by large grass-eating herbivores (graminivores) on mixed grass prairie plant communities was initiated by Dr. Warren C Whitman in 1936. This ongoing long-term project monitors changes in herbage biomass production, plant species composition, and soil characteristics on nongrazed areas inside of barbed wire exclosures compared to grazed areas outside of the exclosures at four two-way rangeland ecological site reference areas.

This report quantitatively describes the effects from long-term nongrazing as determined by differences in plant community characteristics of the nongrazed areas compared to the grazed areas of North Dakota's oldest rangeland reference areas after 75 years and 87 years of treatment.

Development of the Regions Public Grasslands

European settlement of western North Dakota was encouraged by the Homestead Act of 1862 and followed the construction of the first railroad across North Dakota. The Federal Railroad Land Grant Act of 1864 granted the Northern Pacific Railroad 39 million acres of land in a checkerboard pattern from Duluth, Minnesota to Puget Sound, Washington. Construction of the railroad started in 1870 at Superior, Wisconsin and reached Moorhead, Minnesota in December 1871. The tracks reached Bismarck, North Dakota in June 1873, Dickinson in 1880, and the Montana border in 1881. The human population of western North Dakota greatly increased during 1898 to 1915 with the peak period of activity between 1900 and 1910.

Title to 160 acres of surveyed public domain land west of the Mississippi River was transferred from the US Government to private citizens as a provision of the Homestead Act. Several attempts to adjust the law to meet the needs of the people and the natural resources were made. However, none of the many revisions of the Act met the needs of western United States. No instructional information on how to manage these lands was provided to the homesteaders. Failure of the lawmakers to address the requirements of the natural resources in semiarid regions caused numerous long-lasting management problems. In addition, the economic depression of 1929, the severe drought conditions of 1934 and 1936, and the low agricultural commodity prices received during the late 1920's and early 1930's created extreme hardships for homesteaders. The people living on lands declared to be submarginal were given the option to sell their land back to the federal government.

The Taylor Grazing Act of 1934 removed all unappropriated public domain lands from homestead, which included 68,442 acres in North Dakota. The Land Utilization Project was established in 1935 and a resettlement plan was completed that same year. Under these legislative acts, 1,104,789 homesteaded acres were purchased by the US Government in North Dakota (Hibbard 1965; Carstensen 1968; Manske 1994, 2008). The homestead acres repurchased under the Land Utilization Projects were designated for three specific purposes. The lands identified for grazing use and economic development from livestock agriculture became the Little Missouri National Grasslands, the lands identified for recreation use became the Theodore Roosevelt National Park, and the lands identified for

wildlife use became Lostwood National Wildlife Refuge. The Bankhead-Jones Farm Tenant Act of 1937 provided for the implementation of followup conservation and utilization programs and for the development of improved practices of management for the repurchased lands.

Whitman (1953) reported that the United States Department of Agriculture Resettlement Administration authorized the establishment of experimental laboratory areas to conduct research on rangeland management practices for the Land Utilization Project's repurchased acres. Four rangeland reference areas were established in the Pyramid Park Region of the Little Missouri River Badlands in 1936 by an informal agreement. When the USDA Soil Conservation Service took over the administration of the Land Utilization Project, a formal lease agreement was signed in 1939 by the North Dakota Agricultural Experiment Station and the Soil Conservation Service. The lease agreement was for 50 years, and it was automatically renewable every eight years. When the USDA Forest Service took over the administration of the Little Missouri National Grasslands, the agency honored the previous lease agreement and issued an Occupancy Permit in 1955. This Terminable Permit was annually renewable as long as the requirements and conditions were met. To lengthen the term of the permit, the USDA Forest Service issued a Special Use Permit in 1987 to North Dakota State University Agricultural Experiment Station for collection of scientific data on the long term effects of grazing on four typical grassland ecosystems and for related livestock and range research. The permit was reissued in 2005 and requires renewal in 2025 and every twenty years thereafter.

Rangeland Reference Areas

Two-way rangeland reference areas that included a livestock enclosure area and a similar area exposed to livestock grazing were established on four major prairie grassland types based on the classification system developed by Hanson and Whitman (1938). These reference areas have been renamed according to current terminology. The four rangeland reference areas are the oldest scientifically documented reference areas in North Dakota and possibly in the Northern Plains. All four reference areas are located in Billings County, North Dakota, south of the city of Medora in the Pyramid Park Region on the eastern portion of the Little Missouri River Badlands.

The Sandy Ecological Site Reference Area was originally labeled Sandy Upland Rangeland Area and was classified as the Sandgrass Grassland Type, with prairie sandreed (*Calamovilfa longifolia*) as the dominant grass. The reference area is located in Section 15, T 138 N, R 102 W, has slopes of 2% east, northeast, and west, has an enclosure of 6.27 acres, and was constructed in 1937.

The Shallow Ecological Site Reference Area was originally labeled Badlands Upland Rangeland Area and was classified as the Grama-Needlegrass- Sedge Grassland Type, with blue grama (*Bouteloua gracilis*), needle and thread (*Hesperostipa comata*), and upland sedges (*Carex filifolia*, and *Carex inops heliophila*) as the dominant graminoids. The reference area is located in Section 5, T 138 N, R 101 W, has slopes of 3% north, has enclosures of 6.50 acres in two parts (west 4.90 acres, east 1.60 acres), and was constructed in 1937.

The Silty Ecological Site Reference Area was originally labeled Badlands Slope Rangeland Area and was classified as the Western wheatgrass- Grama-Sedge Grassland Type, with blue grama (*Bouteloua gracilis*), western wheatgrass (*Pascopyrum smithii*), and upland sedge (*Carex filifolia*) as the dominant graminoids. The reference area is located in Section 3, T 138 N, R 101 W, has a slope of 3% south, has an enclosure of 14.10 acres, and was constructed in 1938.

The Overflow Ecological Site Reference Area was originally labeled Sagebrush Flat Rangeland Area and was classified as the Sagebrush Type, with silver sagebrush (*Artemisa cana*) as the dominant shrub and western wheatgrass (*Pascopyrum smithii*), blue grama (*Bouteloua gracilis*), and green needlegrass (*Nassella viridula*) as the dominant grasses. The reference area is located in Section 11, T 138 N, R 101 W, has a slope of less than 1%, has an enclosure of 2.90 acres, and was constructed in 1937.

The portions of the reference areas that are outside the enclosures have been annually exposed to grazing by livestock, primarily cow-calf pairs, and managed with moderately stocked, 7 to 8 month seasonlong grazing treatments. The grazing treatments are part of larger grazing units that are allotments in the Little Missouri National Grasslands, administered by USDA Forest Service and managed in cooperation with North Dakota Grazing Associations. Grazing permits for these allotments run from 1 May through 31 December, however, in most years the grazing season has been shortened because of inclement weather conditions.

Long-Term Regional Weather

The western North Dakota region has cold winters and hot summers typical of continental climates. Mean annual temperature is 40.9° F (4.9° C). January is the coldest month, with a mean temperature of 11.5° F (-11.4° C). July and August are the warmest months, with mean temperatures of 68.7° F (20.4° C) and 67.0° F (19.5° C), respectively. Long-term (1892-2010) mean annual precipitation is 16.03 inches (407.15 mm). The precipitation during the perennial plant growing season (April through October) is 13.54 inches (343.92 mm) and is 84.5% of the annual precipitation. June has the greatest monthly precipitation, at 3.55 inches (90.14 mm). The precipitation received in the three month period of May, June, and July is 8.13 inches (206.50 mm) and is 50.7% of the annual precipitation (table 1) (Manske 2011c).

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 (1892-2010) ombrothermic diagram (figure 1) shows near water deficiency conditions during August, September, and October, and favorable water relations during April, May, June, and July. Reoccurrence of water deficiency conditions during April, May, June, and July is 16.9%, 13.6%, 10.2%, and 38.1%, respectively, and during August, September, and October water deficiency reoccurs 52.5%, 50.0%, and 46.6% of the years, respectively. Long-term occurrence of water deficiency conditions is 32.7% of the growing season months, for a mean of 2.0 water deficient months per growing season (Manske et al. 2010).

Table 2 (Manske 2024) shows monthly precipitation for perennial plant growing season months 2011 to 2023. During this 13 year period, 2 growing seasons (15.4%) had drought conditions, 3 growing seasons (23.1%) had wet conditions, and 8 growing seasons (61.5%) had normal conditions. Two growing seasons had water deficiency during 3.5 months, 2 growing seasons had water deficiency during 2.5 months, 2 growing seasons had water deficiency during 2 months, 2 growing seasons had water deficiency during 1 or 0.5 months, and 5 growing seasons had water deficiency during 0 months. The long-term mean monthly rate of water deficiency during the period of 132 years from 1892 is 31.4% of growing season months with water deficiency or 2 months (1.9 mo.) for each perennial plant growing season of 6 months (mid April to mid October). The mean growing season precipitation for this 13 year period was 15.27 inches at 106% of LTM with a mean of 1.4 months with water deficiency per 6 month growing seasons and 5 growing seasons with no water deficiency.

Table 1. Long-term (1892-2010) mean monthly temperature and monthly precipitation in western North Dakota.

	° F	° C	in.	mm
Jan	11.48	-11.40	0.41	10.39
Feb	15.25	-9.31	0.41	10.34
Mar	26.21	-3.22	0.74	18.71
Apr	41.56	5.31	1.41	35.76
May	52.77	11.54	2.34	59.39
Jun	61.96	16.65	3.55	90.14
Jul	68.74	20.41	2.24	56.92
Aug	67.01	19.45	1.71	43.38
Sep	56.09	13.38	1.34	33.97
Oct	43.74	6.52	0.95	24.20
Nov	28.44	-1.98	0.54	13.62
Dec	16.89	-8.39	0.41	10.33
	MEAN		TOTAL	
	40.85	4.91	16.03	407.15

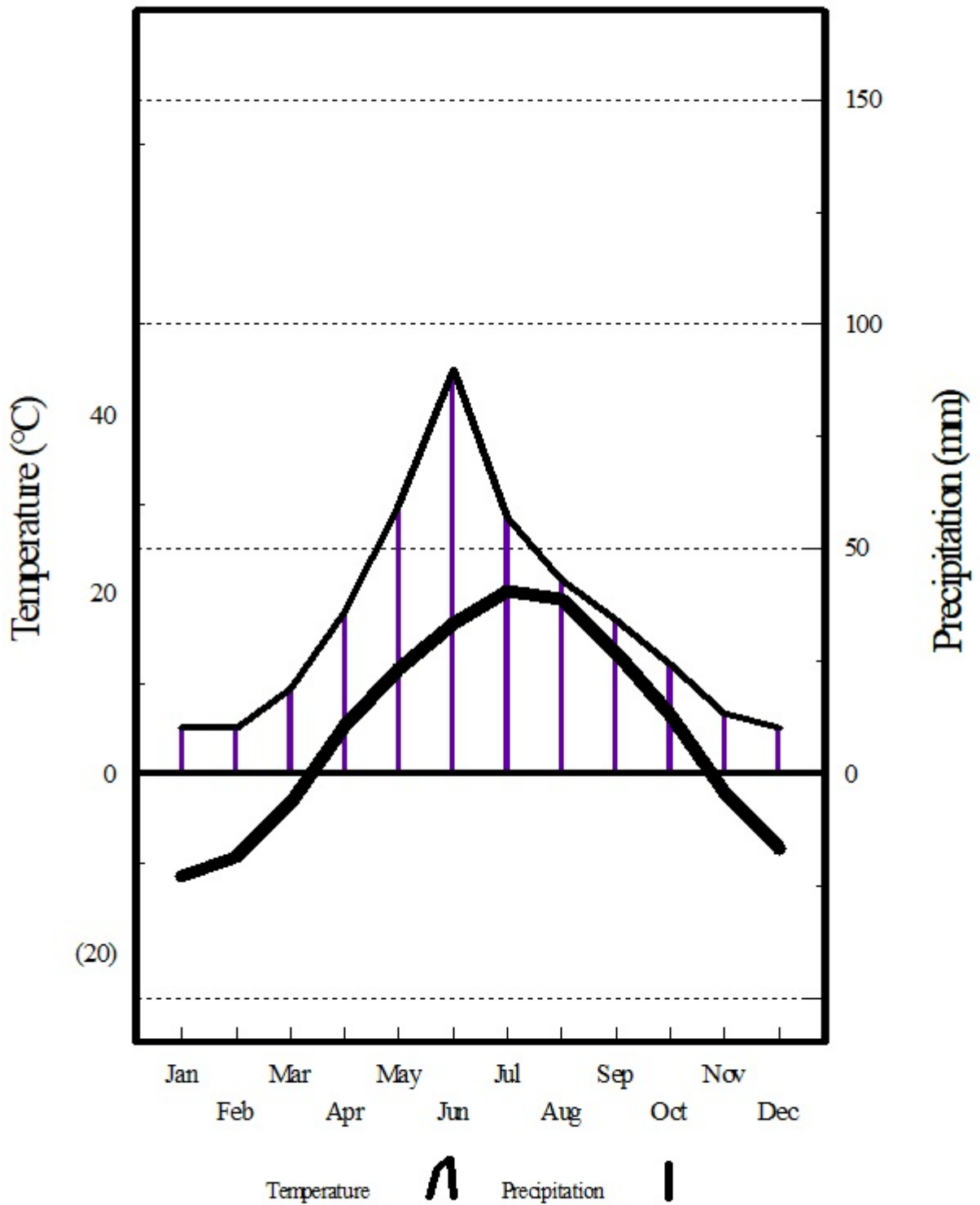


Figure 1. Ombrothermic diagram of long-term (1892-2010) mean monthly temperature and monthly precipitation in western North Dakota.

Table 2. Precipitation in inches and percent of long-term mean for perennial plant growing season months, 2011- 2023.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2023	1.42	2.66	3.04	2.34	1.99	1.62	1.34	14.41	17.06
2011	1.66	6.87	2.15	2.33	2.70	1.76	0.44	17.91	21.28
% of LTM	116.90	258.27	70.72	99.57	135.68	108.64	32.84	124.31	124.74
2012	2.38	1.58	4.31	1.98	0.82	0.21	2.35	13.63	15.46
% of LTM	167.61	59.40	141.78	84.62	41.21	12.96	175.37	94.60	90.62
2013	1.05	7.55	2.23	2.13	2.81	2.44	3.35	21.56	23.22
% of LTM	73.94	283.83	73.36	91.03	141.21	150.62	250.00	149.64	136.11
2014	1.41	3.73	3.38	0.37	8.84	1.03	0.59	19.35	21.11
% of LTM	99.30	140.23	111.18	15.81	444.22	63.58	44.03	134.30	123.74
2015	0.60	1.65	4.68	2.87	1.69	1.35	1.96	14.80	17.01
% of LTM	42.25	62.03	153.95	122.65	84.92	83.33	146.27	102.72	99.71
2016	3.44	2.26	1.96	3.61	1.86	2.66	1.80	17.59	19.70
% of LTM	242.25	84.96	64.47	154.27	93.47	180.95	134.33	122.09	115.47
2017	1.30	0.84	1.27	0.72	2.67	2.28	0.08	9.16	10.55
% of LTM	91.55	31.58	41.78	30.77	134.17	140.74	5.97	63.58	61.84
2018	0.48	1.22	4.23	2.01	0.55	1.84	0.66	10.99	14.39
% of LTM	33.80	45.86	139.14	85.90	27.64	113.58	49.25	76.28	84.35
2019	1.35	2.52	2.60	1.61	4.70	9.10	1.26	23.14	25.88
% of LTM	95.07	94.74	85.53	68.80	236.18	561.73	94.03	160.61	151.70
2020	0.59	1.45	1.10	2.67	2.56	0.86	0.26	9.49	11.01
% of LTM	41.55	54.51	36.18	114.10	128.64	53.09	19.40	65.87	64.54
2021	0.26	5.07	1.07	1.03	1.63	0.14	2.70	11.90	13.75
% of LTM	18.31	190.60	35.20	44.02	81.91	8.64	201.49	82.59	80.60
2022	4.16	3.17	2.02	3.71	0.28	0.93	1.84	16.11	20.16
% of LTM	292.96	119.17	66.45	158.55	14.07	57.41	137.31	111.81	118.17
2023	0.30	2.69	1.91	2.21	3.25	1.32	1.24	12.92	15.42
% of LTM	21.13	101.13	62.83	94.44	163.32	81.48	92.54	89.67	90.39
Mean	1.46	3.12	2.53	2.10	2.64	1.99	1.43	15.27	17.61
% of LTM	102.82	117.41	83.27	89.58	132.82	123.08	106.37	105.99	103.23

Procedures

The effects from long-term nongrazing since 1936 was compared to the effects from seasonlong grazing by large graminivores on four major plant communities of the mixed grass prairie at the two-way rangeland reference areas established by Dr. Warren C. Whitman in 1936. Vegetation changes in aboveground herbage biomass, grass basal cover, forb density, shrub density, belowground plant root biomass, rhizosphere biomass, and available soil mineral nitrogen were evaluated with data collected during the growing season from late June through mid September, 2011 and 2023.

Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986). Vegetation on the grazed areas outside of the exclosures was protected from grazing during the growing season by steel wire quonset type cages measuring 3 X 7 foot placed on the reference areas prior to livestock turnout. The herbage material from five 0.25 m² quadrats (frames) at each sample site both inside (ungrazed) and outside (grazed) each exclosure was hand clipped to ground level and sorted in the field by biotype categories: domesticated grasses, cool-season grasses, warm-season grasses, sedges, forbs, standing dead, and litter. The herbage of each biotype category from each frame was placed in labeled paper bags of known weight, oven dried at 140° F (60° C), and weighed. Herbage biomass in pounds per acre for each category were determined from the clipping data.

Plant species basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986), with 2000 points collected in the near vicinity of long-term transect lines both inside (ungrazed) and outside (grazed) each exclosure. The major transect lines were parallel to each other on opposite sides of the exclosure fence. The minor transect lines were perpendicular to the major transect lines and were parallel to each other. Basal cover plant species data were sorted into biotype categories: domesticated grasses, native grasses, sedges, forbs, woody species, and litter. Native grass species were categorized as cool-season grasses, and warm-season grasses.

Density of forbs were determined by counting individual stems of each forb species rooted inside twenty five 0.1 m² quadrats placed in the near vicinity of long-term transect lines both inside (ungrazed) and outside (grazed) each exclosure. The major transect lines were parallel to each other on opposite sides of the exclosure fence. The minor transect lines were perpendicular to the major transect lines and were parallel to each other. Forb species were categorized for analysis as: late succession forbs, mid succession forbs, and early succession forbs. Density per 0.1 m² quadrat were determined from the forb density data.

Density of shrubs were collected by counting individual plants of each shrub species rooted inside twenty five 1.0 m² quadrats both inside (ungrazed) and outside (grazed) each exclosure. Density per 1.0 m² quadrat were determined from the shrub density data. Because of the huge differences in data from inside and outside the exclosures, this data was not reported. This procedure adequately represented the shrub component of the plant community at the sample sites outside (grazed) each exclosure, however, because of the great extent and high number of woody species growing inside the exclosures, this method greatly undersampled the woody plants located within each exclosure. A species present list of shrubs, cacti, and trees was compiled for inside and outside each exclosure.

Digital plant community maps of the four exclosures were developed. Shrub and tree infested plant communities were separated from grass plant communities into distinct map units on the long-term exclosure areas by ocular assessment of USDA National Agriculture Imagery Program 2009 orthoimages as displayed by Google Earth. Surface area of the woody shrub and tree infested map units and the nonwoody grass map units were determined in acres as digital data in ArcGIS. Technical mapping procedures were completed by student ArcGIS technicians, with direction from Tobias L. Stroh, Assistant Professor, Department of Agriculture and Technical Studies, Dickinson State University, Dickinson, North Dakota.

Belowground plant root biomass was collected inside (ungrazed) and outside (grazed) each exclosure by two replicated soil cores 3 inches (7.6 cm) in diameter and 4 inches (10.2 cm) in depth. The proportion of live and dead roots in the total belowground plant biomass was not known because root material requires considerable time, one to four or more years, to decompose. Root material was separated from soil in a water bath assisted with gentle manual agitation, placed in labeled paper bags of known weight, oven dried at 140° F (60° C), and weighed. Root biomass per volume of soil at a one half foot depth was determined from the soil core root weight data and reported as tons per acre.

Rhizosphere biomass was collected inside (ungrazed) and outside (grazed) each enclosure by three replicated soil cores 3 inches (7.6 cm) in diameter and 4 inches (10.2 cm) in depth using a humane soil beastie catcher (Manske and Urban 2012). The fresh rhizosphere material, which included the rhizosphere organisms, the active plant roots, and the adhered soil particles, was separated from matrix soil by meticulous excavation with fine hand tools. Both wet and dry rhizosphere weights were collected. Rhizosphere biomass per volume of soil at a one half foot depth was determined from the soil core rhizosphere weight data and reported as tons per acre.

Soil mineral nitrogen, nitrate and ammonium, was sampled inside (ungrazed) and outside (grazed) each enclosure by three replicated soil cores with 6 inch (15.2 cm) increments to a 12 inch (30.5 cm) depth collected using a Veihmeyer soil tube with 1 inch (2.5 cm) diameter. Soil cores were placed on ice immediately and were frozen within 4 to 6 hours of collection. Analysis of soil core samples for available mineral nitrogen (NO₃-NH₄) was conducted by the North Dakota State University Soil Testing Laboratory. Total available mineral nitrogen at a one foot depth was determined from the soil core data and reported as pounds per acre.

Early enclosure studies were typically established without replication. Interpretation of treatment effects on plant community characteristics assumes only minor differences in the vegetation of the grazed area and ungrazed area at the time of enclosure construction on each reference area. The number of shrub and tree species present in the grazed area and the ungrazed area were compared.

The Overflow Ecological Site data was not included in this report, this site was originally setup in 1937. After 75 years of treatment there was very little grass cover area remaining. Grass and forb herbage biomass and basal cover and density data were not collected during 2023.

A standard t-test was used to analyze differences among means (Mosteller and Rourke 1973). Nomenclature of plant species on the long- term rangeland reference areas follows Barkworth et al. (2003, 2007).

Results

Sandy Ecological Site

The Sandy Ecological Site (figure 2) was classified by Hanson and Whitman (1938) as the Sandgrass Grassland Type with prairie sandreed, upland sedges, blue grama, needle and thread, and prairie Junegrass as the major vegetation. The loamy fine sand soil was the Blanchard series, mixed, frigid Typic Ustipsamments.

After 75 years, herbage biomass of native grasses was 1272.35 lbs/ac on the grazed area and 341.81 lbs/ac on the ungrazed area, with a 73.1% decrease on the ungrazed area. Herbage biomass of cool season grasses, warm season grasses, and sedges decreased 70.2%, 78.2%, and 59.8%, respectively, on the ungrazed area. Herbage biomass of domesticated grasses was 0.0 lbs/ac on the grazed area and 1158.89 lbs/ac on the ungrazed area, with a 100.0% increase on the ungrazed area. Native grass composition was 66.1% on the grazed area and 18.4% on the ungrazed area. Domesticated grass composition was 0.0% on the grazed area and 62.3% on the ungrazed area. Herbage biomass of forbs was 147.72 lbs/ac on the grazed area and 156.99 lbs/ac on the ungrazed area, with a 6.3% increase on the ungrazed area. Total live herbage biomass was 1925.29 lbs/ac on the grazed area and 1861.07 lbs/ac on the ungrazed area, with a 3.3% decrease on the ungrazed area. Standing dead biomass was 353.23 lbs/ac on the grazed area and 230.49 lbs/ac on the ungrazed area, with 34.8% decrease on the ungrazed area. Litter was 104.90 lbs/ac on the grazed area and 791.38 lbs/ac on the ungrazed area, with a 654.4% increase on the ungrazed area. Total dead biomass was 458.13 lbs/ac on the grazed area and 1021.87 lbs/ac on the ungrazed area, with a 123.1% increase on the ungrazed area. The total aboveground plant biomass was comprised of 35.5% dead biomass on the ungrazed area (table 3).

After 87 years, herbage biomass of native grasses was 606.56 lbs/ac on the grazed area and 341.81 lbs/ac on the ungrazed area, with 43.7% decrease on the ungrazed area. Herbage biomass of cool season, and warm season grasses decreased 16.1% and 59.1% respectively, and sedges increased 93.3% on the ungrazed area. Herbage biomass of domesticated grasses was 5.71 lbs/ac on the grazed area and 439.58 lbs/ac on the ungrazed area, with a 7598.4% increase on the ungrazed area. Native grass composition was 73.2% on the grazed area and 28.9% on the ungrazed area. Domesticated grass composition was 0.7% on the grazed area and 37.2% on the ungrazed area. Herbage biomass of forbs was 46.38 lbs/ac on the grazed area and 72.07 lbs/ac on the ungrazed area, with a 55.4% increase on the ungrazed area. Total live herbage biomass was 828.49 lbs/ac on the grazed area and 1181.72 lbs/ac on the ungrazed area, with a 42.6% increase on the ungrazed area. Standing dead biomass was 271.88 lbs/ac on the grazed area and 148.43 lbs/ac on the ungrazed area, with 45.4% decrease on the ungrazed area. Litter was 887.00 lbs/ac on the grazed area and 1356.56 lbs/ac on the ungrazed area, with a 52.4% increase on the ungrazed area. Total dead biomass was 1158.88 lbs/ac on the grazed area and 1499.99 lbs/ac on the ungrazed area, with a 29.4% increase on the ungrazed area. The total aboveground plant biomass was comprised of 55.9% dead biomass on the ungrazed area (table 3).

After 75 years, basal cover of native grasses was 17.5% on the grazed area and 3.9% on the ungrazed area, with a 78.0% decrease on the ungrazed area. Basal cover of cool season grasses, warm season grasses, and sedges decreased 49.2%, 84.6%, and 39.2%, respectively, on the ungrazed area. Basal cover of domesticated grasses was 0.2% on the grazed area and 5.7% on the ungrazed area, with a 3700.0% increase on the ungrazed area. Native grass had the greatest basal covers on the grazed area and sedges had the greatest basal covers on the ungrazed area. Total live basal cover was 30.2% on the grazed area and 17.0% on the ungrazed area, with a 43.8% decrease on the ungrazed area (table 4).

After 87 years, basal cover of native grasses was 14.4% on the grazed area and 6.1% on the ungrazed area, with a 57.8% decrease on the ungrazed area. Basal cover of cool season grasses, warm season grasses, and sedges decreased 47.1%, 65.7%, and 27.7%, respectively, on the ungrazed area. Basal cover of domesticated grasses was 0.0% on the grazed area and was 7.9% on the ungrazed area, with a 100.0% increase on the ungrazed area. Sedges had the greatest basal cover on both the grazed and ungrazed areas. Total live basal cover was 35.1% on the grazed area and 26.8% on the ungrazed area, with a 23.5% decrease on the ungrazed area (table 4).

After 75 years, total forb density was 5.8 forbs/0.10 m² on the grazed area and 3.5 forbs/0.10 m² on the ungrazed area, with a 40.4% decrease on the ungrazed area. Density of late and early succession forbs decreased 75.8% and 88.9%, respectively, and density of mid succession forbs increased 980.0% on the ungrazed area (table 5).

After 87 years, total forb density was 6.0 forbs/0.10 m² on the grazed area and 0.6 forbs/0.10 m² on the ungrazed area, with a 90.0% decrease on the ungrazed area. Density of late, mid, and early succession forbs decreased 85.3%, 100.0%, and 94.4%, respectively, on the ungrazed area (table 5).

Shrub density collected by the quantitative method greatly undersampled the woody plants located within the enclosure. Compilation of the woody species present list identified one shrub species and two cacti species on the grazed area and five shrub species, two cacti species, and one tree species on the ungrazed area (table 6). A greater number of woody species and a greater number of individual woody plants were present on the ungrazed enclosure than were on the grazed area (figure 3). The ArcGIS mapping procedures identified 2.93 acres (46.7%) of nonwoody grass plant communities and 3.34 acres (53.3%) of woody shrub and tree infested plant communities on the 6.27 acre Sandy Ecological Site enclosure (figure 3 and table 7). The woody plant communities occupy a greater proportion of the ungrazed enclosure.

After 75 years of seasonlong grazing on the sandy ecological site, the aboveground herbage biomass consisted of 80.8% live herbage and 19.2% standing dead and litter. The live herbage was comprised of 0.0% domesticated grass, 66.1% native grasses (41.7% cool season and 24.4% warm season), 26.2% sedges, and 7.5% forbs. After 75 years of nongrazing, the aboveground herbage biomass consisted of 64.6% live herbage and 35.4% standing dead and litter. The live herbage was comprised of 62.3% domesticated grasses, 18.4% native grasses (12.9% cool season and 5.5% warm season), 10.9% sedge, and 8.4% forbs (table 3).

After 87 years of seasonlong grazing on the sandy ecological site, the aboveground herbage biomass consisted of 41.7% live herbage and 58.3% standing dead and litter. The live herbage was comprised of 0.7% domesticated grasses, 73.2% native grasses (26.3% cool season and 46.9% warm season), 20.5% sedges, and 5.6% forbs. After 87 years of nongrazing, the aboveground herbage biomass consisted of 44.1% live herbage and 55.9% standing dead and litter. The live herbage was comprised of 37.2% domesticated grasses, 28.9% native grasses (15.5% cool season and 13.5% warm season), 27.8% sedges, and 6.1% forbs (table 3).



Figure 2. Sandy Ecological Site, located in Sec. 15, T 138 N, R 102 W, enclosure of 6.27 acres, built in 1937, looking North.

Table 3. Herbage biomass (lbs/ac) for native rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Sandy	Herbage Biomass After 75 years			Herbage Biomass After 87 years		
	lbs/ac Grazed	lbs/ac Exclosure	% Difference	lbs/ac Grazed	lbs/ac Exclosure	% Difference
Domesticated	0.00	1158.89	+100.00	5.71	439.58	+7598.42
Cool Season	803.51	239.77	-70.16	217.65	182.68	-16.07
Warm Season	468.84	102.04	-78.24	388.91	159.13	-59.08
Native Grass	1272.35	341.81	-73.14	606.56	341.81	-43.65
Sedges	505.23	203.38	-59.75	169.84	328.26	+93.28
Forbs	147.72	156.99	+6.28	46.38	72.07	+55.39
Total Live	1925.30	1861.07	-3.34	828.49	1181.72	+42.64
Standing Dead	353.23	230.49	-34.75	271.88	148.43	-45.41
Litter	104.90	791.38	+654.41	887.00	1356.56	+52.37
Total Dead	458.13	1021.87	+123.05	1158.88	1499.99	+29.43

Table 4. Basal cover (%) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Sandy	Basal Cover After 75 years			Basal Cover After 87 years		
	% Grazed	% Exclosure	% Difference	% Grazed	% Exclosure	% Difference
Domesticated	0.15	5.70	+3700.00	0.00	7.85	+100.00
Cool Season	3.25	1.65	-49.23	6.05	3.20	-47.11
Warm Season	14.25	2.20	-84.56	8.30	2.85	-65.66
Native Grass	17.50	3.85	-78.00	14.35	6.05	-57.84
Sedges	11.60	7.05	-39.22	17.50	12.65	-27.71
Forbs	0.85	0.35	-58.82	3.05	0.25	-91.80
Total Live	30.15	16.95	-43.78	35.05	26.80	-23.54
Litter	69.85	83.05	+18.90	64.95	73.20	+12.70

Table 5. Forb density (#/0.10 m²) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Sandy Forbs	Forb Density After 75 years			Forb Density After 87 years		
	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference
Late Succession	5.28	1.28	-75.76	3.00	0.44	-85.33
Mid Succession	0.20	2.16	+980.00	0.16	0.00	-100.00
Early Succession	0.36	0.04	-88.89	2.84	0.16	-94.37
Total Live	5.84	3.48	-40.41	6.00	0.60	-90.00

Table 6. Shrubs, cacti, and trees present on the reference areas in the Little Missouri River Badlands.

	Sandy	
	Grazed	Exclosure
<i>Prunus virginiana</i>		X
<i>Rhus trilobata</i>		X
<i>Rosa arkansana</i>	X	X
<i>Symphoricarpos occidentalis</i>		X
<i>Yucca glauca</i>		X
<i>Coryphantha vivipara</i>	X	X
<i>Opuntia polyacantha</i>	X	X
<i>Juniperus scopulorum</i>		X



Figure 3. Sandy Ecological Site enclosure with Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

Table 7. Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

				Major Plant Communities	
Site: Sandy				Nonwoody Grass	Woody Shrub and Tree Infested
		Total Enclosure Area			
Acres	6.27	2.93	3.34		
Percentage		46.67	53.33		

Determined by ArcGIS mapping procedures.

Shallow Ecological Site

The Shallow Ecological Site (figure 4) was classified by Hanson and Whitman (1938) as the Grama-Needlegrass-Sedge Grassland Type with blue grama, needle and thread, upland sedges, western wheatgrass, and prairie Junegrass as the major vegetation. The loamy fine sand soil was the Telfer-Lihen complex, sandy, mixed, frigid Entic Haploborolls.

After 75 years, herbage biomass of native grasses was 798.52 lbs/ac on the grazed area and 26.41 lbs/ac on the ungrazed area, with an 96.7% decrease on the ungrazed area. Herbage biomass of cool season grasses, warm season grasses, and sedges decreased 96.1%, 98.3%, and 46.2%, respectively, on the ungrazed area. Herbage biomass of domesticated grasses was 0.0 lbs/ac on the grazed area and 1299.47 lbs/ac on the ungrazed area, with a 100.0% increase on the ungrazed area. Native grass composition was 62.9% on the grazed area and 1.5% on the ungrazed area. Domesticated grass composition was 0.0% on the grazed area and 72.3% on the ungrazed area. Herbage biomass of forbs was 183.40 lbs/ac on the grazed area and 316.12 lbs/ac on the ungrazed area, with a 72.4% increase on the ungrazed area. Total live herbage biomass was 1269.49 lbs/ac on the grazed area and 1796.84 lbs/ac on the ungrazed area, with a 41.5% increase on the ungrazed area. The quantity of standing dead biomass on the grazed area was almost nonexistent at 3.57 lbs/ac. Standing dead biomass on the ungrazed area was 376.07 lbs/ac, with a 10434.2% increase on the ungrazed area. Litter was 70.65 lbs/ac on the grazed area and 643.67 lbs/ac on the ungrazed area, with an 811.1% increase on the ungrazed area. Total dead biomass was 74.22 lbs/ac on the grazed area and 1019.74 lbs/ac on the ungrazed area, with a 1273.9% increase on the ungrazed area. The total aboveground plant biomass was comprised of 36.2% dead biomass on the ungrazed area (table 8).

After 87 years, herbage biomass of native grasses was 373.21 lbs/ac on the grazed area and 22.83 lbs/ac on the ungrazed area, with a 95.9% decrease on the ungrazed area. Herbage biomass of cool season grasses, warm season grasses, and sedges decreased 92.5%, 95.9%, and 83.1%, respectively, on the ungrazed area. Herbage biomass of domesticated grasses was 37.82 lbs/ac on the grazed area and 1421.49 lbs/ac on the ungrazed area, with a 3658.6% increase on the ungrazed area. Native grass composition was 59.2% on the grazed area and 1.4% on the ungrazed area. Domesticated grass composition was 6.0% on the grazed area and 84.9% on the ungrazed area. Herbage biomass of forbs was 62.80 lbs/ac on the grazed area and 203.38 lbs/ac on the ungrazed area, with a 223.9% increase on the ungrazed area. Total live herbage biomass was 630.11 lbs/ac on the grazed area and 1674.11 lbs/ac on the ungrazed area, with a 165.7% increase on the ungrazed area. Standing dead biomass was 217.65 lbs/ac on the grazed area and 789.96 lbs/ac on the ungrazed area, with a 263.0% increase on the ungrazed area. Litter was 692.11 lbs/ac on the grazed area and 2728.81 lbs/ac on the ungrazed area, with an 294.2% increase on the ungrazed area. Total dead aboveground plant biomass was comprised 67.8% dead biomass on the ungrazed area (table 8).

After 75 years, basal cover of native grasses was 21.9% on the grazed area and 1.2% on the ungrazed area, with a 94.7% decrease on the ungrazed area. Basal cover of cool season grasses and warm season grasses decreased 88.7% and 98.2%, respectively, and basal cover of sedges increased 1.9% on the ungrazed area. Basal cover of domesticated grasses was 0.0% on the grazed area and 5.8% on the ungrazed area, with a 100.0% increase on the ungrazed area. Warm season grasses had the greatest basal cover on the grazed area and upland sedges had the greatest basal cover on the ungrazed area. Total live basal cover was 34.9% on the grazed area and 19.1% on the ungrazed area, with a 45.3% decrease on the ungrazed area (table 9).

After 87 years, basal cover of native grasses was 13.9% on the grazed area and 0.3% on the ungrazed area, with a 98.8% decrease on the ungrazed area. Basal cover of cool season grasses and warm season grasses decreased 89.6%, and 99.6%, respectively, and sedges increased 1.6% on the ungrazed area. Basal cover of domesticated grasses was 1.9% on the grazed area and was 24.3% on the ungrazed area, with a 1179.0% increase on the ungrazed area. Warm season grass had the greatest basal cover on the grazed area and domesticated grass had the greatest basal cover on the ungrazed area. The total live basal cover was 36.4% on the grazed area and 35.2% on the ungrazed area, with a 3.4% decrease on the ungrazed area (table 9).

After 75 years, total forb density was 23.8 forbs/0.10 m² on the grazed area and 9.9 forbs/0.10 m² on the ungrazed area, with a 58.5% decrease on the ungrazed area. Density of late and early succession forbs decreased 82.6% and 90.9%, respectively, and density of mid succession forbs increased 1533.3% on the ungrazed area (table 10).

After 87 years, total forb density was 1.9 forbs/0.10 m² on the grazed area and 5.7 forbs/0.10 m² on the ungrazed area, with a 195.8% increase on the ungrazed area. Density of late season forbs increased 200.0%, mid succession forbs decreased 100.0%, and early succession forbs did not change (table 10).

Shrub density collected by the quantitative method greatly undersampled the woody plants located within the enclosure. Compilation of the woody species present list identified two shrub species on the grazed area and five shrub species and two tree species on the ungrazed area (table 11). A greater number of woody species and a greater number of individual woody plants were present on the ungrazed enclosure than were on the grazed area (figure 5). The ArcGIS mapping procedures identified 2.15 acres (43.9%) of nonwoody grass plant communities and 2.75 acres (56.1%) of woody shrub and tree infested plant communities on the west 4.90 acre Shallow Ecological Site enclosure (figure 5 and table 12). The woody plant communities occupy a greater proportion of the ungrazed enclosure.

After 75 years of seasonlong grazing on the shallow ecological site, the aboveground herbage biomass consisted of 94.5% live herbage and 5.5% standing dead and litter. The live herbage was comprised of 0.0% domesticated grass, 62.9% native grass (45.9% cool season and 17.0% warm season), 22.7% sedge, and 14.5% forbs. After 75 years of nongrazing, the aboveground herbage biomass consisted of 63.8% live herbage and 36.2% standing dead and litter. The live herbage was comprised of 72.3% domesticated grasses, 1.5% native grasses (1.3% cool season and 0.2% warm season), 8.6% sedge, and 17.6% forbs (table 8).

After 87 years of seasonlong grazing on the shallow ecological site, the aboveground herbage biomass consisted of 40.9% live herbage and 59.1% standing dead and litter. The live herbage was comprised of 6.0% domesticated grass, 59.2% native grasses (34.7% cool season and 24.6% warm season), 24.8% sedges, and 10.0% forbs. After 87 years of nongrazing, the aboveground herbage biomass consisted of 32.2% live herbage and 67.8% standing dead and litter. The live herbage was comprised of 84.9% domesticated grass, 1.4% native grass (1.0% cool season and 0.4% warm season), 1.6% sedges, and 12.2% forbs (table 8).



Figure 4. Shallow Ecological Site, located in Sec. 5, T 138 N, R 101 W, enclosure of 6.50 acres, built in 1937.

Table 8. Herbage biomass (lbs/ac) for native rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Shallow	Herbage Biomass After 75 years			Herbage Biomass After 87 years		
	lbs/ac Grazed	lbs/ac Exclosure	% Difference	lbs/ac Grazed	lbs/ac Exclosure	% Difference
Domesticated	0.00	1299.47	+100.00	37.82	1421.49	+3658.57
Cool Season	583.01	22.84	-96.08	218.36	16.41	-92.48
Warm Season	215.51	3.57	-98.34	154.85	6.42	-95.85
Native Grass	798.52	26.41	-96.69	373.21	22.83	-93.88
Sedges	287.58	154.85	-46.15	156.28	26.40	-83.11
Forbs	183.40	316.12	+72.37	62.80	203.38	+223.85
Total Live	1269.49	1796.84	+41.54	630.11	1674.11	+165.69
Standing Dead	3.57	376.07	+10434.17	217.65	789.96	+262.95
Litter	70.65	643.67	+811.07	692.19	2728.81	+294.23
Total Dead	74.22	1019.74	+1273.94	909.84	3518.77	+286.75

Table 9. Basal cover (%) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Shallow	Basal Cover After 75 years			Basal Cover After 87 years		
	% Grazed	% Exclosure	% Difference	% Grazed	% Exclosure	% Difference
Domesticated	0.00	5.80	+100.00	1.90	24.30	+1178.95
Cool Season	7.95	0.90	-88.68	2.40	0.25	-89.58
Warm Season	13.90	0.25	-98.20	11.45	0.05	-99.56
Native Grass	21.85	1.15	-94.74	13.85	0.30	-98.83
Sedges	10.30	10.50	+1.94	9.40	9.55	+1.60
Forbs	2.70	1.55	-42.59	11.25	0.90	-92.00
Total Live	34.85	19.05	-45.34	36.40	35.15	-3.43
Litter	62.65	75.90	+21.15	47.75	60.25	+26.18

Table 10. Forb density (#/0.10 m²) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Shallow	Forb Density After 75 years			Forb Density After 87 years		
	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference
Forbs						
Late Succession	22.52	3.92	-82.59	1.88	5.64	+200.00
Mid Succession	0.36	5.88	1533.33	0.04	0.00	-100.00
Early Succession	0.88	0.08	-90.91	0.00	0.00	-
Total Live	23.76	9.88	-58.42	1.92	5.68	+195.83

Table 11. Shrubs, cacti, and trees present on the reference areas in the Little Missouri River Badlands.

	Shallow	
	Grazed	Exclosure
<i>Artemisia cana</i>		X
<i>Prunus virginiana</i>		X
<i>Rhus trilobata</i>		X
<i>Rosa arkansana</i>	X	X
<i>Symphoricarpos occidentalis</i>	X	X
<i>Fraxinus pennsylvanica</i>		X
<i>Juniperus scopulorum</i>		X

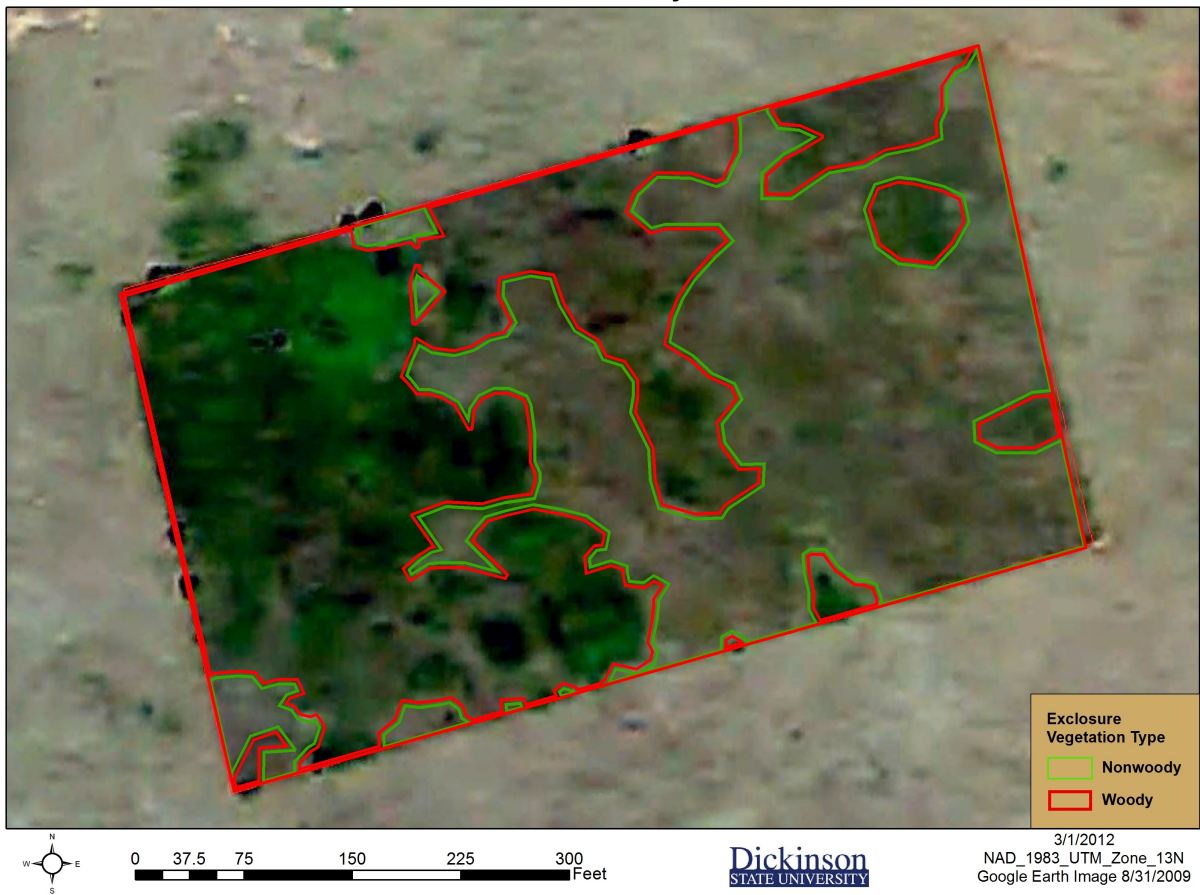


Figure 5. Shallow Ecological Site enclosure with Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

Table 12. Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

Major Plant Communities			
Site: Shallow	Total Enclosure Area	Nonwoody Grass	Woody Shrub and Tree Infested
Acres	4.90	2.15	2.75
Percentage		43.90	56.10

Determined by ArcGIS mapping procedures.

Silty Ecological Site

The Silty Ecological Site (figure 6) was classified by Hanson and Whitman (1938) as the Wheatgrass-Grama-Sedge Grassland Type with western wheatgrass, blue grama, upland sedge, needle and thread, and prairie Junegrass as the major vegetation. The silt loam soil was a Farland-like series, fine-silty, mixed, superactive, Typic Argiborolls.

After 75 years, herbage biomass of native grasses was 707.90 lbs/ac on the grazed area and 102.04 lbs/ac on the ungrazed area, with a 85.6% decrease on the ungrazed area. Herbage biomass of cool season grasses, warm season grasses, and sedges decreased 80.0%, 99.7%, and 23.9%, respectively, on the ungrazed area. Herbage biomass of domesticated grasses was 692.91 lbs/ac on the grazed area and 1427.91 lbs/ac on the ungrazed area, with a 106.1% increase on the ungrazed area. Native grass composition was 42.3% on the grazed area and 5.7% on the ungrazed area. Domesticated grass composition was 41.4% on the grazed area and 79.6% on the ungrazed area. Herbage biomass of forbs was 124.88 lbs/ac on the grazed area and 149.86 lbs/ac on the ungrazed area, with a 20.0% increase on the ungrazed area. Total live herbage biomass was 1674.82 lbs/ac on the grazed area and 1793.28 lbs/ac on the ungrazed area, with a 7.1% increase on the ungrazed area. Standing dead biomass was 112.04 lbs/ac on the grazed area and 494.52 lbs/ac on the ungrazed area, with a 341.4% increase on the ungrazed area. Litter was 563.03 lbs/ac on the grazed area and 2162.21 lbs/ac on the ungrazed area, with a 284.0% increase on the ungrazed area. Total dead biomass was 675.07 lbs/ac on the grazed area and 2656.73 lbs/ac on the ungrazed area, with a 293.6% increase on the ungrazed area (table 13). The total aboveground plant biomass was comprised of 59.7% dead biomass on the ungrazed area. The ungrazed area had 48.2% greater total dead biomass than total live herbage biomass.

After 87 years, herbage biomass of native grasses was 214.79 lbs/ac on the grazed area and 209.80 lbs/ac on the ungrazed area, with a 2.3% decrease on the ungrazed area. Herbage biomass of cool season grasses and sedges increased 1.1% and 148.3% respectively, and warm season grasses decreased 43.5% on the ungrazed area. Herbage biomass of domesticated grasses was 1160.31 lbs/ac on the grazed area and 850.61 lbs/ac on the ungrazed area, with a 26.7% decrease on the ungrazed area. Native grass composition was 13.0% on the grazed area and 17.8% on the ungrazed area. Domesticated grass composition was 70.5% on the grazed area and 72.3% on the ungrazed area. Herbage biomass of forbs was 109.18 lbs/ac on the grazed area and 312.56 lbs/ac on the ungrazed area, with a 186.3% increase on the ungrazed area. Total live herbage biomass was 1646.99 lbs/ac on the grazed area and 1176.86 lbs/ac on the ungrazed area, with a 7.9% decrease on the ungrazed area. Standing dead biomass was 301.85 lbs/ac on the grazed area and 473.12 lbs/ac on the ungrazed area, with 56.7% increase on the ungrazed area. Litter was 692.91 lbs/ac on the grazed area and 1582.05 lbs/ac on the ungrazed area, with a 128.3% increase on the ungrazed area. Total dead biomass was 994.76 lbs/ac on the grazed area and 2055.17 lbs/ac on the ungrazed area, with a 106.6% increase on the ungrazed area (table 13). The total aboveground plant biomass was comprised of 63.6% dead biomass on the ungrazed area. The ungrazed area had 74.6% greater total dead biomass than total live herbage biomass.

After 75 years, basal cover of native grasses was 6.0% on the grazed area and 0.0% on the ungrazed area, with a 100.0% decrease on the ungrazed area. Basal cover of cool season grasses, warm season grasses, and sedges decreased 100.0%, 100.0%, and 79.8%, respectively, on the ungrazed area. Basal cover of domesticated grasses was 17.5% on the grazed area and 11.7% on the ungrazed area, with a 33.2% decrease on the ungrazed area. The domesticated grass basal cover on the grazed area was 49.6% greater than the basal cover on the ungrazed area, however, the domesticated grass herbage biomass on the grazed area was 51.5% less than the herbage biomass on the ungrazed area, indicating that the domesticated grass tillers on the grazed area were numerous but small compared to the large and robust domesticated grass tillers on the ungrazed area. Total live basal cover was 30.1% on the grazed area and 15.2% on the ungrazed area, with a 49.4% decrease on the ungrazed area (table 14).

After 87 years, basal cover of native grasses was 6.6% on the grazed area and 2.4% on the ungrazed area, with a 64.1% decrease on the ungrazed area. Basal cover of cool season grasses, warm season grasses, and sedges decreased 55.4%, 79.2%, and 43.1%, respectively, on the ungrazed area. Basal cover of domesticated grasses was 21.0% on the grazed area and 17.9% on the ungrazed area, with a 15.0% decrease on the ungrazed area. The domesticated grass basal cover on the grazed area was 17.6% greater than the basal cover on the ungrazed area and

the domesticated grass herbage biomass was 36.4% greater on the grazed area than that on the ungrazed area, indicating that the grazed area had degraded greater than the ungrazed area. Total live basal cover was 39.5% on the grazed area and 29.1% on the ungrazed area, with a 26.3% decrease on the ungrazed area (table 14). The native grass composition was 16.6% on the grazed area and 8.1% on the ungrazed area, with 51.2% decrease on the ungrazed area. The domesticated grass composition was 53.2% on the grazed area and 61.3% on the ungrazed area, with a 15.2% increase on the ungrazed area.

After 75 years, total forb density was 10.5 forbs/0.10 m² on the grazed area and 12.8 forbs/0.10 m² on the ungrazed area, with a 22.1% increase on the ungrazed area. Density of late succession forbs increased 145.3% and density of mid and early succession forbs decreased 92.5% and 100.0%, respectively, on the ungrazed area (table 15).

After 87 years, total forb density was 1.2 forbs/0.10 m² on the grazed area and 5.6 forbs/0.10 m² on the ungrazed area, with a 370.0% increase on the ungrazed area. Density of late succession forbs increased 386.2%, density of mid succession forbs decreased 100.0%, and density of early succession forbs remained at 0.0% (table 15).

Shrub density collected by the quantitative method greatly undersampled the woody plants located within the enclosure. Compilation of the woody species present list identified two shrub species on the grazed area and nine shrub species, one cactus species, and two tree species on the ungrazed area (table 16). A greater number of woody species and a greater number of individual woody plants were present on the ungrazed enclosure than were on the grazed area (figure 7). The ArcGIS mapping procedures identified 6.52 acres (46.2%) of nonwoody grass plant communities and 7.58 acres (53.8%) of woody shrub and tree infested plant communities on the 14.10 acre Silty Ecological Site enclosure (figure 7 and table 17). The woody plant communities occupy a greater proportion of the ungrazed enclosure.

After 75 years of seasonlong grazing on the silty ecological site, the aboveground herbage biomass consisted of 71.3% live herbage and 28.7% standing dead and litter. The live herbage was comprised of 41.4% domesticated grass, 42.3% native grass (30.3% cool season and 12.0% warm season), 8.9% sedges, and 7.5% forbs. After 75 years of nongrazing, the aboveground herbage biomass consisted of 40.3% live herbage and 59.7% standing dead and litter. The live herbage was comprised of 79.6% domesticated grasses, 5.7% native grass (5.66% cool season and 0.04% warm season), 6.3% sedge and 8.4% forbs (table 13).

After 87 years of seasonlong grazing on the silty ecological site, the aboveground herbage biomass consisted of 62.3% live herbage and 37.7% standing dead and litter. The live herbage was comprised of 70.5% domesticated grasses, 13.0% native grasses (12.0% cool season and 1.0% warm season), 9.9% sedge, and 6.6% forbs. After 87 years of nongrazing, the aboveground herbage biomass consisted of 36.4% live herbage and 63.6% standing dead and litter. The live herbage was comprised of 72.3% domesticated grasses, 17.8% native grasses (17.0% cool season and 0.8% warm season), 34.3% sedges, and 26.6% forbs (table 13).



Figure 6. Silty Ecological Site, enclosure with increased woody vegetation, located in Sec. 3, T138N, R101W, enclosure of 14.10 acres, built in 1938.

Table 13. Herbage biomass (lbs/ac) for native rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Silty	Herbage Biomass After 75 years			Herbage Biomass After 87 years		
	lbs/ac Grazed	lbs/ac Exclosure	% Difference	lbs/ac Grazed	lbs/ac Exclosure	% Difference
Domesticated	692.91	1427.91	+106.07	1160.31	850.61	-26.69
Cool Season	506.66	101.33	-80.00	198.38	200.52	+1.08
Warm Season	201.24	0.71	-99.65	16.41	9.28	-43.45
Native Grass	707.90	102.04	-85.58	214.79	209.80	-2.32
Sedges	149.14	113.46	-23.93	162.70	403.90	+148.25
Forbs	124.88	149.86	+20.00	109.18	312.56	+186.28
Total Live	1674.82	1793.28	+7.07	1646.99	1176.86	-7.89
Standing Dead	112.04	494.52	+341.38	301.85	473.12	+56.74
Litter	563.03	2162.21	+284.03	692.91	1582.05	+128.32
Total Dead	675.07	2656.73	+293.55	994.76	2055.17	+106.60

Table 14. Basal cover (%) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Silty	Basal Cover After 75 years			Basal Cover After 87 years		
	% Grazed	% Exclosure	% Difference	% Grazed	% Exclosure	% Difference
Domesticated	17.45	11.65	-33.24	21.00	17.85	-15.00
Cool Season	3.25	0.00	-100.00	4.15	1.85	-55.42
Warm Season	2.75	0.00	-100.00	2.40	0.50	-79.17
Native Grass	6.00	0.00	-100.00	6.55	2.35	-64.12
Sedges	5.70	1.15	-79.82	11.25	6.40	-43.11
Forbs	0.90	2.40	+166.67	0.70	2.45	+250.00
Total Live	30.05	15.20	-49.42	39.50	29.10	-26.33
Litter	64.25	84.80	+31.98	53.80	70.90	+31.78

Table 15. Forb density (#/0.10 m²) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands, 2011 and 2023.

Site: Silty	Forb Density After 75 years			Forb Density After 87 years		
	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference	#/0.10 m ² Grazed	#/0.10 m ² Exclosure	% Difference
Forbs						
Late Succession	5.12	12.56	+145.31	1.16	5.64	+386.21
Mid Succession	3.20	0.24	-92.50	0.04	0.00	-100.00
Early Succession	2.16	0.00	-100.00	0.00	0.00	-
Total Live	10.48	12.80	+22.14	1.20	5.64	+370.00

Table 16. Shrubs, cacti, and trees present on the reference areas in the Little Missouri River Badlands.

	Silty	
	Grazed	Exclosure
<i>Artemisia cana</i>		X
<i>Juniperus communis</i>		X
<i>Juniperus horizontalis</i>		X
<i>Prunus virginiana</i>		X
<i>Rhus trilobata</i>		X
<i>Rosa arkansana</i>	X	X
<i>Shepherdia argentea</i>		X
<i>Symphoricarpos occidentalis</i>	X	X
<i>Yucca glauca</i>		X
<i>Opuntia polyacantha</i>		X
<i>Fraxinus pennsylvanica</i>		X
<i>Juniperus scopulorum</i>		X



Figure 7. Silty Ecological Site enclosure with Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

Table 17. Woody shrub and tree infested plant communities and Nonwoody grass plant communities in the Little Missouri River Badlands.

Site: Silty	Major Plant Communities		
	Total Enclosure Area	Nonwoody Grass	Woody Shrub and Tree Infested
Acres	14.10	6.52	7.58
Percentage		46.23	53.77

Determined by ArcGIS mapping procedures.

Belowground Characteristics

The deteriorating effects from long-term nongrazing on the mixed grass prairie plant communities of three reference area exclosures on the sandy, shallow, and silty sites were great.

Total belowground plant root biomass on the three sites was 20.82 tons/ac on the grazed area and 13.14 tons/ac on the ungrazed area, with a 36.9% decrease on the ungrazed area (table 18).

Rhizosphere biomass on the three sites was 104.78 tons/ac on the grazed area and 90.61 tons/ac on the ungrazed area, with a 13.5% decrease on the ungrazed area (table 19).

Soil available mineral nitrogen ($\text{NO}_3\text{-NH}_4$) on the three sites was 37.09 lbs/ac on the grazed area and 35.60 lbs/ac on the ungrazed area, with 4.0% decrease on the ungrazed area (table 20).

Compilation of the woody species present list for the three reference sites identified two shrubs and two cacti species present on the grazed area and nine shrubs, two cacti, and two tree species were present on the ungrazed area (table 21).

The ArcGIS mapping procedures of the three reference sites identified 45.6% of the exclosures with nonwoody grass plant communities and 54.4% of the exclosures with woody shrub and tree infested plant communities (table 22).

After 75 years of seasonlong grazing the three reference sites, the live herbage biomass consisted of 14.2% domesticated grass, 57.1% native grass (38.9% cool season and 18.2% warm season), 19.3% sedge, and 9.4% forbs. After 75 years of nongrazing on the three reference sites, the live herbage biomass consisted of 71.3% domesticated grass, 8.6% native grass (6.7% cool season and 2.0% warm season), 8.7% sedge, and 11.4% forbs (table 23). After 87 years of seasonlong grazing on the three reference sites, the live herbage biomass consisted of 38.8% domesticated grass, 38.5% native grass (20.4% cool season and 18.0% warm season), 15.7% sedge, and 7.0% forbs. After 87 years of nongrazing on the three reference sites, the live herbage biomass consisted of 58.5% domesticated grass, 12.4% native grass (8.6% cool season and 3.8% warm season), 16.4% sedge, and 12.7% forbs (table 23).

After 75 years of long-term nongrazing, the native grass herbage biomass decreased 83.1% and basal cover decreased 89.0%. The domesticated grass herbage biomass increased 460.9% and basal cover increased 31.5%. After 87 years of long-term nongrazing, the native grass herbage biomass decreased 51.9% and basal cover decreased 75.0%. The domesticated grass herbage biomass increased 125.3% and basal cover increased 118.5%. (tables 23 and 24).

Table 18. Belowground plant root biomass in ton/ac on three reference areas in the Little Missouri River Badlands.

Ecological Reference Area	tons/ac Grazed	tons/ac Exclosure	% Difference
Sandy	22.09	9.76	-55.82
Shallow	23.48	18.27	-22.19
Silty	16.88	11.38	-32.58
Mean of three	20.82	13.14	-36.89

Table 19. Rhizosphere biomass in ton/ac on three reference areas in the Little Missouri River Badlands.

Ecological Reference Area	tons/ac Grazed	tons/ac Exclosure	% Difference
Sandy	116.29	70.55	-39.33
Shallow	103.77	111.45	+7.40
Silty	94.27	89.82	-4.72
Mean of three	104.78	90.61	-13.52

Table 20. Soil available mineral nitrogen (nitrate and ammonium) in lbs/ac for native rangeland on three reference areas in the Little Missouri River Badlands.

Ecological Reference Area	lbs/ac Grazed	lbs/ac Exclosure	% Difference
Sandy	31.52	23.52	-25.38
Shallow	33.12	41.26	+24.58
Silty	46.62	42.02	-9.87
Mean of three	37.09	35.60	-4.02

Table 21. Shrubs, cacti, and trees present on the three reference areas in the Little Missouri River Badlands

	Three Ecological Sites	
	Grazed	Exclosure
<i>Artemisia cana</i>		X
<i>Juniperus communis</i>		X
<i>Juniperus horizontalis</i>		X
<i>Prunus virginiana</i>		X
<i>Rhus trilobata</i>		X
<i>Rosa arkansana</i>	X	X
<i>Shepherdia argentea</i>		X
<i>Symphoricarpos occidentalis</i>	X	X
<i>Yucca glauca</i>		X
<i>Coryphantha vivipara</i>	X	X
<i>Opuntia polyacantha</i>	X	X
<i>Fraxinus pennsylvanica</i>		X
<i>Juniperus scopulorum</i>		X

Table 22. Acres and percentages of nonwoody and woody plant communities on the three exclosure areas in the Little Missouri River Badlands.

Ecological Site	Exclosure Total		Nonwoody Acres	Woody Acres	Nonwoody %	Woody %
	Area Acres					
Sandy	6.27		2.93	3.34	46.67	53.33
Shallow west	4.90		2.15	2.75	43.90	56.10
Silty	14.10		6.52	7.58	46.23	53.77
Mean of 3	8.42		3.87	4.55	45.60	54.40

Table 23. Herbage biomass (lbs/ac) for native rangeland reference sites, est. 1936, in the Little Missouri River Badlands.

Site:	Herbage Biomass After 75 years			Herbage Biomass After 87 years		
	lbs/ac	lbs/ac	%	lbs/ac	lbs/ac	%
Mean of 3 sites	Grazed	Exclosure	Difference	Grazed	Exclosure	Difference
Domesticated	230.97	1295.42	+460.86	401.28	903.89	+125.25
Cool Season	631.06	121.31	-80.78	211.46	133.20	-37.01
Warm Season	295.20	35.44	-87.99	186.72	58.28	-68.79
Native Grass	926.26	156.75	-83.08	398.19	191.48	-51.91
Sedges	313.98	157.40	-49.87	162.94	252.85	+55.18
Forbs	152.00	207.66	+36.62	72.79	196.00	+169.27
Total Live	1623.20	1817.06	+11.94	1035.20	1544.23	+49.17
Standing Dead	156.28	367.03	+134.85	263.79	470.50	+78.36
Litter	246.19	1199.09	+387.06	757.37	1889.14	+149.43
Total Dead	402.47	1566.11	+289.12	1021.16	2357.98	+130.91

Table 24. Basal cover (%) for rangeland reference sites, est. 1936, in the Little Missouri River Badlands.

Site:	Basal Cover After 75 years			Basal Cover After 87 years		
	%	%	%	%	%	%
Mean of 3 sites	Grazed	Exclosure	Difference	Grazed	Exclosure	Difference
Domesticated	5.87	7.72	+31.52	7.63	16.67	+118.48
Cool Season	4.82	0.85	-82.37	4.20	1.77	-57.86
Warm Season	10.30	0.82	-92.04	7.38	1.13	-84.67
Native Grass	15.12	1.67	-88.96	11.58	2.90	-74.96
Sedges	9.20	6.23	-32.28	12.72	9.53	-25.08
Forbs	1.48	1.43	-3.38	5.00	1.20	-76.00
Total Live	31.68	17.07	-46.12	36.98	30.35	-17.93
Litter	65.58	81.25	+23.89	55.50	68.12	+22.74

Discussion

Removal of cattle grazing does not promote development of stable climax plant communities and does not preserve prairie grasslands in perpetuity. Mixed grass prairie communities deprived of large grazing animals decline steadily into unhealthy disfunctional ecosystems with severe reductions of native grasses, considerable decreases of desirable forbs, enormous increases of introduced domesticated grasses, remarkable increases of woody shrubs and trees, and excessive increases of standing dead and litter as a result of diminished grass plant internal grass growth mechanisms, degraded ecosystem biogeochemical processes, and low grass plant resource uptake competitiveness. Activation of the internal grass growth mechanisms, the ecosystem biogeochemical processes, and grass resource competitiveness requires partial defoliation by large grazing herbivores (graminivores). Grazing animals are essential annual growing season components of rangeland ecosystems.

Traditionally, rangeland ecosystems have been managed from the perspective of the “use” of the grassland. Livestock grazing along with watershed, wildlife, and recreation were considered to be the major uses. Management of rangelands from the perspective of a single use or for multiple uses narrowly considers only a few ecosystem components directly related with these primary uses or products removed. Management for a use does not consider rangelands as complex ecosystems and neglects to address the needs of all other ecosystem components. Management of rangelands for a use, no matter how noble, results in degradation of the ecosystems. The uses of rangeland resources should not be the objective of management. The management should be the means to accomplish the uses. Management strategies need to be designed to beneficially stimulate all ecosystem components to function at potential levels.

Rangelands are complex ecosystems consisting of numerous interactive biotic (living) and abiotic (nonliving) components. The biotic components are the grass plants, soil organisms, and large grazing graminivores that have biological and physiological requirements. The abiotic components include the essential major elements of carbon, hydrogen, nitrogen, and oxygen in the presence of sunlight that have transformable characteristics through biogeochemical processes. Rangeland ecosystems are functioning units of coacting biotic organisms interacting with the abiotic components and the environment. The complex of mechanisms and processes connected with these extensive interactions have been identified as Internal Grass Growth Mechanisms and biogeochemical processes. If any of the numerous processes are not functioning at potential level, the ecosystem does not function at potential level. Management of rangeland ecosystems needs to meet the biological and physiological requirements of the biotic components and stimulate the biogeochemical processes that cycle the abiotic components. Mixed grass prairie communities require biologically effective partial defoliation by annually managed grazing animals in order to persist as healthy and productive ecosystems. Thus, providing the means to accomplish the uses of watershed, wildlife habitat, recreation, and livestock forage at the same time on fully functional rangeland ecosystems.

Implementation of a biologically effective grazing management strategy that stimulates the internal grass growth mechanisms will meet the biological and physiological requirements of the biotic components and will stimulate the biogeochemical processes that cycle the abiotic components (Manske 2011b). The four main internal grass growth mechanisms are: compensatory internal physiological grass growth processes, internal vegetative reproduction of secondary tillers from axillary buds, nutrient resource uptake, water use efficiency, and external symbiotic rhizosphere organism activity (McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995; Manske 1999, 2018).

The internal grass growth mechanisms developed early during the coevolution of grass plants and grazing graminivores (McNaughton 1979, 1983; Coleman et al. 1983; Briske 1991; Briske and Richards 1995; Manske 1999, 2018) and are a complex assemblage of biogeochemical and physiological processes that involve intricate interactions among rhizosphere microorganisms, grass plants, and large grazing graminivores. Activation of these mechanisms provides important biological and physiological processes permitting native grasses to produce greater herbage biomass and to increase basal cover; these mechanisms also enable grass plants to replace lost leaf material, to restore disrupted physiological processes, and to vegetatively reproduce secondary tillers from axillary buds after partial defoliation by grazing. The internal grass growth mechanisms function at variable levels of activation depending on the quantity of available mineral nitrogen in grassland ecosystem soil. When mineral nitrogen is available at 100 lbs/ac or greater, the internal grass growth mechanisms function at full activation. When mineral

nitrogen is available at less than 100 lbs/ac, the internal grass growth mechanisms function at levels less than full activation (Manske 2009). In addition, the water (precipitation) use efficiency processes decrease in grass plants growing in ecosystems with less than 100 lbs/ac available mineral nitrogen causing herbage biomass production to be reduced by 49.6% (Wight and Black 1972, 1979).

The quantity of available mineral nitrogen in grassland ecosystem soils is dependent on the rate of mineralization of soil organic nitrogen by rhizosphere organisms. The larger the rhizosphere volume and microorganism biomass, the greater the quantity of soil mineral nitrogen converted. Rhizosphere volume and microorganism biomass are limited by access to simple carbohydrates (Curl and Truelove 1986). 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 at vegetative phenological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbohydrates to be released from the grass lead 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 results in greater rates of mineralization of soil organic nitrogen converting greater quantities of available mineral nitrogen (Coleman et al. 1983, Klein et al. 1988, Burrows and Pflieger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005). Mineral nitrogen available in quantities of 100 lbs/ac or greater allows defoliated grass tillers full activation of the internal grass growth mechanisms (Manske 2009). Full activation of the compensatory internal physiological processes within grass plants accelerates growth rates of replacement leaves and shoots, increases photosynthetic capacity of remaining mature leaves, increases allocation of carbon and nitrogen, increases nutrient resource uptake, improves water (precipitation) use efficiency, and increases restoration of biological and physiological processes enabling rapid and complete recovery of partially defoliated grass tillers. Full activation of the asexual internal processes of vegetative reproduction increases secondary tiller development from axillary buds and increases initiated tiller density during the grazing season. Full activation of the external symbiotic rhizosphere organism activity increases mineralization of mineral nitrogen, increases ecosystem biogeochemical cycling of essential elements, and improves belowground resource uptake competitiveness (Wight and Black 1972, 1979; McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995; Manske 1999, 2018; Kochy and Wilson 2000).

Biologically effective grazing management strategies have 4.5 month grazing seasons on native grasslands between early June and mid October with 2 grazing periods in each of the 3 to 6 pastures and the rotation dates coordinate partial defoliation by grazing with grass phenological growth stages. Removal of about 25% to 33% of the aboveground leaf material of grass lead tillers between the 3.5 new leaf stage and the flower stage increases the quantity of carbon exudates released through the roots into the rhizosphere, enlarges the rhizosphere volume to 227.06 ft³/ac, increases rhizosphere biomass to 964 tons/ac, and raises rates of mineralization of soil organic nitrogen into mineral nitrogen to 177.84 lbs/ac (Manske 2009, 2011b). The partially defoliated grass tillers in grassland ecosystems with abundant quantities of available mineral nitrogen respond positively to grazing because the internal grass growth mechanisms function at the high levels of full activation that results in complete recovery of defoliated tillers replacing leaf and stem material at 140% greater quantities than that removed by grazing, increasing total tiller density and herbage production, and fully restoring, and then maintaining, the biogeochemical processes and the health of the grassland ecosystem (Manske 2009, 2010b, 2011a).

Traditional grazing management practices with 4.5 month grazing seasons on native grasslands between early June and mid October, but with no rotation dates or rotation dates that are not coordinated with grass phenological growth stages cause slow deterioration of the ecosystems. The antagonistic grazing defoliation results in decreases in the quantities of carbon exudates released through the roots into the rhizosphere, reducing the rhizosphere volume to 67.61 ft³/ac, decreasing the organism biomass and activity, and reducing the rates of mineralization of soil organic nitrogen into mineral nitrogen to 76.70 lbs/ac. The grazed grass tillers in grassland ecosystems with deficient quantities of available mineral nitrogen respond negatively to grazing because the internal grass growth mechanisms function at reduced levels of less than full activation that results in incomplete recovery of grazed tillers replacing less leaf and stem material than the quantity removed by grazing decreasing total tiller density and herbage production, and causing a slow steady decline in the biogeochemical processes and the grassland ecosystem health (Manske 2011a).

Traditional grazing management practices with 6.0 month grazing seasons on native grasslands starting before early June and continuing past mid October, and no rotation dates or rotation dates that are not coordinated with grass phenological growth stages are harmful to the perennial native grass plants, the rhizosphere organisms, and the ecosystem biogeochemical processes. This highly antagonistic defoliation by grazing causes reductions in the quantity of plant carbon exudation through the roots into the rhizosphere. The rhizosphere volume diminishes greatly to 49.75 ft³/ac, reducing the organism biomass and activity, and decreasing the quantities of soil organic nitrogen converted into mineral nitrogen to 61.61 lbs/ac. The grazed grass tillers in grassland ecosystems with insufficient quantities of mineral nitrogen respond negatively to grazing because the internal grass growth mechanisms and biogeochemical processes are activated at extremely low levels (Manske 2009, 2010a) and plant recovery from grazing is incomplete with limited amounts of leaf and stem material replaced, decreasing grass tiller density and herbage production greatly, and causing deterioration in the grassland ecosystem health (Manske 2011a).

Developed grazing management practices with 4.0 month grazing seasons on a deferred native grassland pasture between mid July and mid November that, by design, delays grazing until grass tillers are mature with most producing seeds. This extremely antagonistic grazing defoliation suppresses the amount of carbon exudates released through the roots into the rhizosphere, shrinking the rhizosphere volume and organism biomass, and reducing the rates of mineralization of soil organic nitrogen into mineral nitrogen to 31.20 lbs/ac. The grazed grass tillers in grassland ecosystems with inadequate quantities of mineral nitrogen respond negatively to grazing because the internal grass growth mechanisms and biogeochemical processes barely function. Tiller development and herbage biomass production are extremely low. Numerous undesirable plants invade the native communities and the grassland ecosystem health degrades to low condition (Manske 2011a).

Nondefoliation management by complete rest of mixed grass prairie ecosystems is not a revitalizing inactivity. Removing graminivores from grassland ecosystems to provide rest from grazing is a devitalizing activity that results in decreased rhizosphere organism biomass causing deficiencies in mineral nitrogen and other essential elements, and that results in decreased sunlight intensity and soil water causing deficiencies in fixed carbon and vital organic compounds.

After 1936, the healthy native grass communities in the four reference area exclosures started to deteriorate as a result of withholding grazing by large graminivores. Soon after grazing graminivores had been removed from the grasslands, the native grass live root biomass decreased (Whitman 1974), standing dead leaves and litter accumulated (Brand and Goetz 1986), and ecosystem biogeochemical processes declined (Manske 2011b).

The reduction of live root surface area causes a decrease in active root length for interaction with symbiotic rhizosphere organisms and causes a decrease in absorption of water and nutrients from the soil. Reduction of active root biomass and diminishment of grass plant health vigor result in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water (Kochy 1999, Kochy and Wilson 2000). The loss of active root length is a contributing factor in the reduction of rhizosphere biomass. The primary cause for the reduction in rhizosphere biomass is, however, the great reduction in the quantity of carbohydrates exuded from the grass roots into the rhizosphere zone. Without partial defoliation by grazing, only a small quantity of short carbon chain energy leaks from the grass roots into the rhizosphere; this low amount of simple carbon compounds is barely enough to sustain a small rhizosphere biomass. A small biomass of rhizosphere organisms mineralize small quantities of nitrogen and other essential elements (Coleman et al. 1983, Klein et al. 1988).

Rhizosphere organism biomass and activity are limited by access to simple carbon chain energy (Curl and Truelove 1986) because the microflora trophic levels lack chlorophyll and have low carbon (energy) content. Partial defoliation by large grazing graminivores of grass lead tillers at vegetative phenological growth stages is required to cause greater quantities of exudates containing simple carbon compounds to be released through the grass roots into the rhizosphere. Biomass and activity of the microorganisms increase with the increase in availability of energy from simple carbon compounds in the rhizosphere. The increase in rhizosphere organism biomass and activity causes an increase in mineralization of nitrogen and other essential elements. Termination of annual partial defoliation by graminivores depletes these substantive processes resulting in deficiencies in mineral nitrogen and other essential elements.

An evolutionary survival mechanism of grass plants in response to partial defoliation and the loss of leaf area as forage to grazing graminivores is the production of double the quantity of leaf biomass than needed for normal plant growth and maintenance (Crider 1955, Coyne et al. 1995). This survival mechanism does not stop upon removal of grazing graminivores. Without grazing graminivores to remove half of the herbage production, the surplus leaf material accumulates rapidly and changes from an asset to a detriment. The accumulation of nondefoliated live and standing dead leaves of grasses reduce light penetration below native grass light saturation points (Peltzer and Kochy 2001). Native grasses have high light saturation points and require near full sunlight. Warm season grasses have higher light saturation points than cool season grasses (Kochy 1999, Kochy and Wilson 2000). Shading reduces native warm season grasses more than native cool season grasses. Introduced cool season domesticated grasses have lower light saturation points than native grasses, permitting domesticated grasses to live in low light conditions.

Low amounts of sunlight reaching native grass leaves decrease the rate of photosynthesis, which reduces the quantity of atmospheric carbon dioxide fixed, reducing the quantity of simple carbohydrates produced (Coyne et al. 1995). Low quantities of carbohydrates cause decreases in growth of roots, leaves, and stems, and development of secondary tillers. Low quantities of carbohydrates also cause increases in the rates of leaf senescence and increases in tiller mortality that results in reductions of native grass plant density (basal cover) and reductions of herbage biomass production (Langer 1972, Grant et al. 1983, Briske and Richards 1995).

The rapidly accumulating quantities of standing dead biomass cannot make contact with the soil surface and decompose quickly through microbial activity. The standing dead biomass decreases slowly by leaching and weathering and builds up into a thick mulch layer. Thick mulch effectively blocks sunlight from reaching understory young grass leaves. Thick mulch insulates the soil from warm spring air temperatures preventing heating of cold soil that causes delays in plant and soil organism activity. Thick mulch ties up and holds organic nutrients above the soil surface preventing accession to the soil organic matter which limits nutrient cycling through biogeochemical processes increasing the deficiencies of essential elements. Thick mulch absorbs and holds precipitation for later evaporation preventing the water from infiltrating into the soil diminishing soil water to deficiency quantities (Wright and Bailey 1982, Manske 2000, 2011a). These undesirable modifications to the ecosystem cause decreases in soil microorganism biomass and activity resulting in further reductions in the rates of organic material decomposition (Anderson et al. 1981, Curl and Truelove 1986, Whipp 1990).

Grass plants developed several physiological, biological, and biogeochemical processes early during coevolution with graminivores in response to partial defoliation and the removal of leaf area (McNaughton 1979, 1983; Coleman et al. 1983; Briske 1991; Briske and Richards 1995; Manske 1999). This set of processes are collectively recognized as internal grass growth mechanisms (Briske 1991, Briske and Richards 1995). Annual partial defoliation by grazing graminivores of grass lead tillers at growth stages between the 3.5 new leaf stage and the flower stage is required to activate the internal grass growth mechanisms.

Native grass plants need the essential major elements of carbon, hydrogen, nitrogen, and oxygen in the presence of sunlight for physiological growth processes to produce leaves, stems, roots, and secondary tillers (Manske 2011b). Removal of grazing graminivores from grasslands and the failure to activate the internal grass growth mechanisms restricts grass plants use of important mechanisms and processes necessary for normal grass growth and development.

The carbon allocated for grass growth does not come from stored material in the roots but is carbon recently fixed (Richards and Caldwell 1985, Coyne et al. 1995, Briske and Richards 1995). The carbon comes from atmospheric carbon dioxide which composes about 0.03% of the gasses in the atmosphere and exists at concentrations of around 385 to 412 mg/kg. Atmospheric carbon dioxide is not limiting on rangelands. The carbon dioxide is fixed with hydrogen from soil water during the process of photosynthesis which converts energy from sunlight into chemical energy and assimilates simple carbohydrates. However, when nondefoliated live and standing dead leaves of grasses reduce sunlight reaching understory grass leaves, photosynthetic rates are greatly reduced and available fixed carbon becomes deficient.

The hydrogen allocated for grass growth comes from soil water absorbed through the roots. Soil water is infiltrated precipitation. In western North Dakota, the perennial plant growing season months have a long-term

periodicity rate of water deficiency conditions at 32.7%, for a mean of 2.0 months with water deficiency per growing season (Manske et al. 2010). The thick mulch that builds up on nondefoliation managed grasslands causes additional soil water problems. Thick mulch intercepts a portion of the precipitation inhibiting infiltration. The thicker the mulch, the greater the quantity of the precipitation absorbed. Absorption of the precipitation by the mulch causes a deficiency in soil water further inhibiting carbon assimilation.

The nitrogen allocated for grass growth can be mobilized from shoot and root tissue (Briske and Richards 1995) when the preferential source of mineral nitrogen recently converted from soil organic nitrogen by active rhizosphere organisms is low. Low quantities of available soil mineral nitrogen below 100 lbs/ac is the major limiting factor of herbage growth on rangelands (Wight and Black 1979). However, mixed grass prairie soils are not deficient of nitrogen. Most of the nitrogen is immobilized in the soil as organic nitrogen. Untilled grassland soils contain about 3 to 8 tons of organic nitrogen per acre. Soil organic nitrogen must be mineralized by rhizosphere organisms to become plant usable mineral nitrogen. The quantity of rhizosphere organisms is the limiting factor in grassland ecosystems low in mineral nitrogen. Biomass and activity of organisms in the rhizosphere are limited by access to energy from simple carbohydrates which can be exudated from grass leaf tillers with partial defoliation by grazing graminivores when grass tillers are at vegetative growth stages. Available mineral nitrogen becomes extremely deficient when grazing graminivores are removed from a grassland.

Light is radiant energy from the sun and is necessary for photosynthesis. Intensity of sunlight can be greatly reduced by shading from other plants. Nondefoliated live and standing dead leaves of grasses reduce light penetration to a similar degree as shrubs, even though shrub leaves are flat and wide and grass leaves are erect and linear (Kochy 1999). The light levels penetrating the leaf canopy can be about 20% of the light levels above the canopy (Peltzer and Kochy 2001).

Nondefoliation of native grass plants reduces exudation of short carbon chain energy to slow leakage into the rhizosphere, reducing biomass and activity of soil organisms, decreasing mineralization processes that cause deficiencies in mineral nitrogen and other essential elements. Failure to remove the double produced leaf biomass annually causes shading that greatly reduces the sunlight intensity reaching native grass leaves, reducing photosynthetic rates that cause deficiencies in available fixed carbon. Accumulation of undecomposed grass leaf material modifies soil temperatures, causes deficiencies in soil water, and causes additional deficiencies in essential elements. The deficiencies of indispensable component resources of carbon, hydrogen, nitrogen, oxygen, and other essential elements prevent grass plants from synthesizing sufficient quantities of vital carbohydrates, proteins, and nucleotides. Without sufficient quantities of vital organic compounds native grass plants cannot maintain production of herbage biomass and tiller numbers (Langer 1972, Briske and Richards 1995).

Advanced degradation by antagonistic nondefoliation management of mixed grass prairie communities results in creation of numerous large bare spaces between native grass plants in the plant community. These open spaces, that lack competition from native grasses, are ideal habitat for growth of introduced cool season domesticated grasses like Kentucky bluegrass, and smooth brome grass, and for growth of other opportunistic “weedy” plant species. These introduced plants have labile roots that break down easily making the nutrients contained in dead roots readily available to support continued growth and expansion of these nonnative plants without assistance from symbiotic rhizosphere organisms. The composition of plant species changes with decreases in the desirable species and increases in less desirable species, and later with increases in undesirable species. The change in plant composition from desirable to undesirable species is actually the symptom of ecosystem degradation; the fundamental degradation is the diminishment of internal grass growth mechanisms within grass plants, decrease of ecosystem biogeochemical processes, and the reduction of available mineral nitrogen below 100 lbs/ac. The degree of plant species change lags behind the degree of ecosystem biogeochemical degradation.

Nondefoliation management can degrade mixed grass prairie more drastically than poor grazing management. Removal of cattle grazing from mixed grass prairie plant communities causes discontinuation of internal grass growth mechanisms, degeneration of ecosystem biogeochemical processes, depletion of plant species composition with severe reductions of native grasses, excessive increases of standing dead and litter, extreme increases of introduced domesticated grasses, remarkable increases of woody shrub and tree species, and degradation of range condition to very low percentages of potential climax vegetation after 75 and 87 years of long-term nongrazing.

A remarkably high quantity of woody shrub and tree species and an exceptionally great number of individual woody plants were able to develop on the four reference area ungrazed exclosures because the competitive advantage of grasses for belowground resources was diminished in conjunction with the degradation of the native grass plant communities that resulted from removal of grazing defoliation by large graminivores. The existence of a shrub component in a grassland plant community is not an ecological beneficial relationship. Shrubs and grasses are adversarial inhibitive competitors. Grasses and shrubs compete for sunlight, mineral nitrogen, and soil water.

The degree of difference in competitive abilities between prairie grasses and shrubs on the mixed grass prairie was investigated during 1994 to 1998 at the University of Regina, Saskatchewan, with direction from Dr. S.D. Wilson. The grass growth form has competitive advantages over the shrub growth form. The per gram of biomass effects on resource use efficiency are smaller for shrub growth forms than for grass growth forms (Kochy and Wilson 2000). Shrubs must use a portion of the photosynthates produced in the leaves to build and maintain their unproductive woody stems; the result is a great reduction in resource uptake efficiency. Shrubs require 6 times greater aboveground biomass than the grasses before grass production is decreased as a result of competition from the shrubs (Kochy 1999). Grass aboveground biomass is primarily productive photosynthetic leaves; the result is a high resource uptake efficiency. Grasses have a 1.4 times greater per gram of biomass resource efficiency effect than shrubs (Kochy 1999). Grasses on prairie habitat attenuated more light, took up more mineral nitrogen, and took up more soil water per gram of biomass than did shrubs on brush habitat (Kochy 1999, Kochy and Wilson 2000). Because grasses have high root : shoot ratios and no woody stems to maintain; grasses are good competitors for belowground resources and superior competitors for mineral nitrogen. Shrub's taller growth form makes the plants superior competitors for aboveground resources (Kochy and Wilson 2000).

Competition between shrubs and grasses during early stages of shrub expansion into prairie habitat of healthy grasses is primarily for belowground resources of nutrients and soil water; under these initial conditions, grasses have the advantage and the shrubs are suppressed (Kochy and Wilson 2000, Peltzer and Kochy 2001). Competition from healthy grasses also reduces the growth rates of shrub rhizomes and causes high mortality rates of young suckers, preventing expansion into healthy grass communities (Li and Wilson 1998). Seedlings of grasses and shrubs are also unable to compete effectively for resources in healthy established grass plant communities and are suppressed (Peltzer and Kochy 2001). Successful competition of grasses for belowground resources prevents shrubs from becoming established in healthy grass communities. Shrubs can compete for some of the belowground resources only after the grass plants have been degraded by antagonistic management practices.

Following the reduction in grass plant resource competitiveness, establishment of shrubs can occur in degraded grasslands, which frequently starts as clumps (Li and Wilson 1998). The belowground resources previously used by the healthy robust grasses, but no longer consumed by the smaller, less vigorous degraded grasses, are taken up by the shrub plants resulting in proportional increases of biomass production (Kochy and Wilson 2000). After grass competition for belowground resources is reduced, shrub rhizome suckers can regain the faster growth rates and higher survival rates (Li and Wilson 1998) resulting in greater shrub stem densities. As shrub stem density increases, the competition shifts to primarily the aboveground resources of light; under these different degraded conditions, shrubs have the advantage and the grasses are strongly suppressed (Kochy and Wilson 2000).

The reduction of the competitiveness of the grasses for belowground resources of mineral nitrogen and soil water in conjunction with diminution of the internal grass growth mechanisms and degradation of the biogeochemical processes in the grass plant communities that resulted from the antagonistic nondefoliation management practices fully explains the extraordinary increase of woody shrubs and trees growing in the four ungrazed exclosures.

The increase of woody shrubs and trees in grass communities would have traditionally been explained as a result of fire suppression (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). The grazed areas and the ungrazed exclosures of the four reference areas have all had at least 75 and 87 years without fire defoliation. However, if fire suppression had caused the increase of shrubs and trees, the quantity of woody plants would have been nearly similar on the ungrazed and grazed areas. The ungrazed exclosures have had a far greater intrusion of woody plants than the grazed areas. The grazed grasses have maintained a greater degree of competitiveness than the ungrazed grasses. The greater increase of woody plants into the grass communities of the

ungrazed exclosures has not been the result of fire suppression. The increased woody plant infestation of the exclosures has been caused by the greatly reduced competitiveness of the ungrazed grasses and the degradation of the biogeochemical processes in the grass plant communities that resulted from the removal of partial defoliation by large grazing graminivores.

Many ecologists have observed that the repeated occurrence of fire was the force that prevented intrusion of shrubs and trees into grasslands (Weaver 1954, Humphrey 1962, Daubenmire 1974, Stoddart, Smith, and Box 1975, Wright and Bailey 1982), and, the obvious corollary, that suppression of fire has facilitated the invasion of shrubs and trees into grasslands (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). However, the presence of fire does not prove that grasslands need or are caused by fire (Heady 1975). In the northern mixed grass prairie, fire cannot prevent the invasion of or cause the removal of shrubs and trees that reproduce by vegetative secondary suckers growing from crown (stem base) or rhizome buds (Wright and Bailey 1982, Manske et al. 2006a, Manske 2006b). Almost all deciduous woody plants growing in the Northern Plains grassland reproduce vegetatively.

The increase of undesirable introduced herbaceous grasses and forbs in grass communities has also often times been explained as a result of fire suppression (Wright and Bailey 1982). Kirsch and Kruse (1972) concluded that the cool season exotic grasses, Kentucky bluegrass and smooth brome grass, have invaded much of the northern mixed grass prairie in the absence of fire. Seedlings of trees, shrubs, weedy forbs, and introduced grasses cannot become established in healthy functioning grassland ecosystems with grasses that have retained full resource uptake competitiveness (Peltzer and Kochy 2001). Establishment of intrusive seedlings can occur only after the grass communities have been degraded by antagonistic management practices. Furthermore, fire cannot prevent establishment and expansion of undesirable seedlings into degraded grass communities unless the fire frequency suppresses seed production of all invasive species in a region.

Repeated prescribed fire can change the percent composition of the aboveground vegetation biomass in degraded mixed grass prairie invaded by shrubs. The composition of introduced cool season grasses, early succession and weedy forbs, and shrub aerial stems decrease temporarily from four repeated every-other-year prescribed fires (Manske 2007a, 2011a). However, the fundamental problems of low native grass competitiveness, diminished internal grass growth mechanisms, and degraded biogeochemical processes remain in the grassland ecosystems following repeated fire events.

None of the physiological and asexual processes of the internal grass growth mechanisms within grass plants and none of the biogeochemical processes performed by symbiotic rhizosphere organisms within grassland ecosystems are activated by fire. Fire does not stimulate vegetative reproduction by tillering. Fire does not stimulate endomycorrhizal fungal colonization of perennial grass roots. Fire does not stimulate rhizosphere organism biomass and activity. Fire does not stimulate mineralization of soil organic nitrogen into mineral nitrogen (Manske 2007a, 2011a, 2018). Fire does not replace partial defoliation by grazing for management of healthy and productive rangeland ecosystems.

Had the early grassland ecologists known about the conclusions from the grass-shrub competition research conducted at the University of Regina and understood the internal grass growth mechanisms and the biogeochemical processes, it would appear extremely plausible that the conjectural observations of increasing shrubs and trees and undesirable forbs and grasses in grassland communities that were explained as results of fire suppression, would have been scientifically explained as shrubs and trees and introduced forbs and grasses effectively competing for a portion of the belowground resources of nutrients and soil water after the competitiveness of the grasses had been reduced as a result of degradation of the grass community caused by antagonistic management practices. The key to woody shrub and tree and herbaceous plant control in grass communities is to regain the competitive advantage of the grasses by restoration of the mechanisms and processes in the mixed grass prairie ecosystem that results from biologically effective partial defoliation by large grazing graminivores.

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