Evaluation of the Importance of Mineral Nitrogen in Restoration of Severely Degraded Mixed Grass Prairie Ecosystems

Llewellyn L. Manske PhD
Research Professor of Range Science
North Dakota State University
Dickinson Research Extension Center
Report DREC 15-1091

Grass plants produce stems, leaves, and roots from vital organic compounds of carbohydrates, proteins, and nucleotides which are comprised of major essential elements, carbon, hydrogen, nitrogen, and oxygen and minor essential elements, macronutrients and micronutrients plus energy from sunlight. Procurement and cycling of the major and minor essential elements occurs through the numerous complex processes of the defoliation resistance mechanisms and biogeochemical processes that requires extensive interactions among the grass plants, soil microorganisms, and grazing graminivores.

Any factor that causes the ecosystem processes to not function properly causes the quantity of essential elements to decrease resulting in reduced ecosystem productivity. Low mineral nitrogen available at quantities less than the threshold of 100 lbs/ac is the major growth limiting factor of native grassland ecosystems and causes ecosystem degradation down to the level of available mineral nitrogen (Manske 1999, 2011, 2014). Removal of grazing graminivores results in severe degradation of native grassland ecosystems.

The objectives of this study are to show the importance of mineral nitrogen to be available at quantities of 100 lbs/ac or greater in restoration of degraded native grassland ecosystems.

Study Area

The native rangeland study sites were on the Schnell Recreation Area (SRA) managed by the USDI Bureau of Land Management (BLM) since 1993, and were located in eastern Stark County approximately 2 miles (3.22 kilometers) east of Richardton, North Dakota, USA.

The western North Dakota region near Richardton has cold winters and hot summers typical of continental climates. Long-term mean annual temperature was 43.0° F (6.1° C). January was the coldest month, with a mean of 13.5° F (-10.3° C). July and August were the warmest months, with mean temperatures of 70.0° F (21.1° C) and 68.9° F (20.5° C), respectively. Long-term (1971-2000) mean annual precipitation was 17.8 inches (451.6 mm). The amount of precipitation received during the perennial plant growing season (April to October) was 14.8 inches (375.7 mm) and was 83.2% of annual precipitation. The precipitation received in the three month period of May, June, and July was 8.2 inches (207.0 mm) and was 45.8% of the annual precipitation.

The native rangeland vegetation was the Wheatgrass-Needlegrass Type (Barker and Whitman 1988, Shiflet 1994) of the mixed grass prairie. The dominant native range grasses were western wheatgrass (Agropyron smithii) (Pascopyrum smithii), needle and thread (Stipa comata) (Hesperostipa comata), blue grama (Bouteloua gracilis), and threadleaf sedge (Carex filifolia).

Management Treatments

The study area was degraded native mixed grass prairie. The area was a working cattle ranch prior to 1993. The entire area was managed exclusively for recreation during the 13 year period of 1993 to 2005 with no cattle grazing permitted. The rangeland ecosystems became severely degenerated by the nondefoliation with complete rest management that was antagonistic to ecosystem biogeochemical processes reducing native plant density, opening plant communities to subsequent invasion by undesirable introduced cool season domesticated grasses, primarily smooth bromegrass, crested wheatgrass, and Kentucky bluegrass.

A study was conducted to evaluate the restoration of severely degraded native mixed grass prairie managed with the twice-over rotation grazing management strategy. Three grassland pastures were grazed from early June until mid October, with each pasture grazed for two periods. Each of the three pastures in the rotation were grazed for 14 to 16 days during the first period, the 45 day interval from 1 June to 15 July. During the second period, the 90 day interval from mid July to mid October, each pasture was grazed for double the number of days that it was grazed during the first period. A fourth pasture was not grazed and was used as a control. Nongrazed 4 was dominated by Kentucky bluegrass; Grazed pasture 3 was dominated by smooth bromegrass; and Grazed pastures 1 and 2 were dominated by Kentucky bluegrass; thus forming the 3 treatments of the study.

Procedure

Temperature and precipitation data were taken from climatological data collected at the Richardton Abbey, Stark County, latitude 46.88° N, longitude 102.31° W at 2467 feet (752 mm) above sea level, 2006-2011.

Grazing pressure determined by animal unit equivalent, herd weight, and stocking rate were assessed at the start of the study using the then current ecological site maps, and were assessed a second time using updated ecological site maps.

Restoration of degraded mixed grass prairie was evaluated on silty ecological sites with permanent sample plots organized in a paired-plot design. Two adjacent plots were at every site, each 16' X 32' (4.88 m X 9.75 m) in size with one grazed and the other ungrazed inside a stock panel exclosure.

Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986) at each pasture rotation date (seven periods per year). The herbage biomass was partially defoliated by the selected twice-over rotation grazing treatment on pasture 3 and pastures 1 & 2. The nongrazed 4 area had no defoliation treatments. The reported herbage biomass values represent the residuum vegetation and the regrowth vegetation resulting from the respective treatments. Clipped herbage material was collected from five 0.25 m^2 quadrats (frames) at silty ecological sample sites for each of the study treatments during the first study section, 2006 to 2011, and during the second study section, 2013 to 2014. The herbage material in each frame was hand clipped to ground level and sorted in the field by biotype categories: domesticated grass, cool season grass, warm season grass, 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. Domesticated grass and native grass (cool and warm season grass) herbage biomass weights were reported for this study.

Plant species basal cover for individual species were determined by the ten-pin point frame method (Cook and Stubbendieck 1986), with 2000 points collected along permanent transect lines at silty ecological sites for each of the study treatments annually during peak growth between mid July and mid August during the first study section, 2006 to 2011, and during the second study section, 2013 to 2014. Basal cover plant species data were sorted into biotype categories: domesticated grass, cool season grass, warm season grass, upland sedges, forbs, and litter. Domesticated grass and native grass (cool season and warm season grass) percent basal cover were reported for this study.

Rhizosphere biomass was collected on silty ecological sites for each of the study treatments during the first study section, 2006 to 2011. Sample areas had been grazed by the twice-over rotation treatment on pasture 3 and on pastures 1 & 2. The nongrazed 4 area had no defoliation treatments. Three replicated soil cores 3 inches (7.6 cm) in diameter and 4 inches (10.2 cm) in depth were collected at each study site during 3 grazing season periods: pregrazing (May), first rotation (July), and second rotation (October) 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 was determined from the soil core rhizosphere weight data and reported as kilograms per cubic meter. Reference samples of rhizosphere weights on silty ecological sites managed long-term with a twice-over rotation grazing strategy were collected by the same methods during 2006 resulting in mean reference rhizosphere weights at 406.44 kg/m^3.

Soil mineral nitrogen, nitrate (NO_3) and ammonium NH_4), was determined from two replicated soil core samples collected at silty ecological sites outside exclosures exposed to the selected twice-over rotation grazing treatment on pasture 3 and on pastures 1 & 2. The nongrazed 4 area had no defoliation treatments. Soil cores were collected with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches on monthly periods during May to October of the second study section, 2013 to 2014. Analysis of soil core samples for available mineral nitrogen (NO_3 and NH_4) was conducted by the North Dakota State University Soil Testing Laboratory. Mean available mineral nitrogen was reported as pounds per acre.

Transformation (immobilization) of nitrate (NO_3) and of ammonium (NH_4) was determined by the net mineralization measurement of the nitrogen balance equation of a soil-plant system (Bloem et al. 2006). The quantity of mineral nitrogen in a soil is the net difference between the total quantity of organic nitrogen mineralized by soil microorganisms and the quantity of mineral nitrogen immobilized by plants and soil microbes (Brady 1974, Legg 1975). The general nitrogen balance equation is simply: the quantity of nitrogen at time 2 minus the quantity of nitrogen at time 1, the difference is the quantity of the transformed nitrogen. Nitrogen quantity at time 1 is the May values. Nitrogen quantity at time 2 is the values at each successive month. Transformed nitrogen is the quantity of uptake by plants and soil microbes and converted into organic nitrogen plus the quantity of nitrogen loss by leaching or volatilization. Loss by leaching on Northern Plains prairies is negligible (Power 1970, Brady 1974, Wight and Black 1979, Coyne et al. 1995). Loss by volatilization during 2013 and 2014 with high soil water content would also be negligible. Transformation of ammonium (NH_4) could include some conversion to nitrate (NO_3). Most of the transformed nitrogen would be the quantity converted into organic nitrogen by plants and soil microbes.

A standard t-test was used to analyze differences among means (Mosteller and Rourke 1973).

Results

Precipitation during the 2006 to 2011 grazing seasons at Richardton, ND was slightly below normal during 2006 and 2007, and was normal during 2008 to 2011. A dry period occurred during May through August 2006. High rainfall occurred during April, May, and July 2011. The mean six year growing season precipitation was 12.3 inches (83.2% of LTM) (table 1). Mean April through July precipitation was 82.8% of LTM and mean August through October precipitation was 84.1% of LTM. Generally, precipitation was normal but a little below average.

The stocking rate used to graze the three pastures of the Schnell Recreation Area was originally intended to be at 75%, 85%, and 95% of the assessed stocking rate during the first three years and then remain at less than 100% for the duration of the study. Cow-calf pairs grazed during the first three years at 72.3%, 82.6%, and 107.5%, with a mean of 87.4%, of the assessed stocking rate. As the cow herd stocking rates increased during the first three years, the relative composition of native grass herbage biomass and basal cover also increased on the grazed pastures. Heifers grazed during 2009 and 2010 at 79.8% and 87.4%, respectively, with a mean of 83.6% of the assessed stocking rate. The reduction in stocking rate of the heifers resulted in a decrease in the relative composition of native grass herbage biomass and basal cover. Steers grazed during 2011 at 37.8% of the assessed stocking rate (table 2). This low stocking rate resulted in a large decrease in the relative composition of native grass herbage biomass and basal cover. The light to moderate stocking rates were not beneficial for improvement of native grass herbage biomass and basal cover.

Degradation of the native grass plant community not only decreased grass plant basal cover but also decreased plant stature. The invading Kentucky bluegrass and smooth bromegrass increased in basal cover and plant stature causing greatly reduced sunlight intensities reaching understory native grass leaves. Getting sunlight to native grass leaves requires annual removal of large quantities of herbage biomass from the dominating introduced domesticated grasses. Relatively high stocking rates are required. Stocking rates greater than 100% can remove great quantities of domesticated grass herbage in a short time period but this is more harmful than helpful. The native grasses can not respond any faster than the rate of increase of the rhizosphere microorganism biomass. However, weedy forbs have mechanisms that can initiate extreme increases to greater sunlight and larger bare spaces and remain problems for many years. Stocking rates less than 85% do not remove enough domesticated grass herbage to effectively reduce the shading problem. Shaded native grasses do not improve but continue to decline. Stocking rates between 85% and 100% remove enough domesticated grass herbage biomass to permit an increased intensity of sunlight to reach the leaves of native grasses that increases the photosynthetic rates and fixes carbon at greater quantites that more closely matches the rate of increase in available mineral nitrogen mineralized by the increasing rhizosphere microorganism biomass.

The mixed grass prairie study area of nongrazed control 4 was a degraded silty ecological site dominated by Kentucky bluegrass. At the start of the study, the aboveground vegetation biomass consisted of 72.3% standing dead and litter and 27.7% live herbage. The live herbage biomass was 95.2% domesticated grasses and 2.1% native grasses.

After 6 growing seasons, the aboveground vegetation biomass consisted of 61.7% standing dead and litter and 38.3% live herbage. The live herbage was 85.1% domesticated grasses and 7.7% native grasses.

Domesticated grass herbage production on nongrazed 4 started early and generally continued to increase through the growing season with peak or near peak production during mid October. Annual herbage biomass production of domesticated grass on nongrazed 4 was not significantly different during 2006, 2007, 2009, 2010, and 2011 growing seasons. Domesticated grass biomass during 2008 was significantly less than that produced during the 2006, 2007, 2009, and 2011 growing seasons (tables 3 and 9). The reduction in domesticated grass production during 2008 was caused by water deficiency conditions during October 2007, and April and May 2008 (table 1). Domesticated grass herbage production on nongrazed 4 was significantly greater than that on pasture 3 during the 2007, 2008, and 2009 growing seasons and significantly greater than that on pastures 1 & 2 during all six growing seasons (tables 9 and 11). Mean basal cover of domesticated grass was 12.97% on nongrazed 4 that was not significantly different than that on pasture 3 and significantly greater than that on pastures 1 & 2 (tables 9 and 11).

Native grass herbage production on nongrazed 4 was low with monthly biomass at less than 500 lbs/ac. Annual herbage biomass production of native grass on nongrazed 4 was not significantly different during the 2006, 2007, 2009, 2010, and 2011 growing seasons (tables 4 and 10). During the 2008 growing season, native grass herbage biomass production was reduced as a result of water deficiency conditions (table 1). Native grass biomass during 2008 was significantly less than that produced during 2009. Native grass biomass on nongrazed 4 was significantly greater that that on pasture 3 during the 2007, 2009, and 2010 growing seasons and significantly lower than native grass biomass on pastures 1 & 2 during the 2011 growing season (table 10). Mean basal cover of native grass on nongrazed 4 was 1.46%, that was significantly greater than that on pasture 3 and significantly less than that on pastures 1 & 2 (tables 10 and 11).

The mixed grass prairie study area of grazed pasture 3 was a degraded silty ecological site dominated by smooth bromegrass and Kentucky bluegrass. At the start of the study, the aboveground vegetation biomass consisted of 68.0% standing dead and litter and 32.0% live herbage. The live herbage biomass was 93.9% domesticated grasses and 2.1% native grasses. After 6 grazing seasons, the aboveground vegetation biomass consisted of 35.6% standing dead and litter and 64.4% live herbage. The live herbage was 89.6% domesticated grasses and 3.5% native grasses.

Domesticated grass herbage production on pasture 3 was abundant usually peaking early during June. Annual herbage biomass production of domesticated grass on pasture 3 was not significantly different during the 2006, 2007, 2009, and 2010 growing seasons. Domesticated grass biomass during 2008 was significantly less than that produced during the 2006, 2009, and 2011 grazing seasons (tables 5 and 9). Some of the reduction in domesticated grass herbage production during 2008 was caused by water deficiency conditions during October 2007, and April and May 2008 (table 1). However, a large portion of the reduction in domesticated grass herbage biomass resulted from the affects of three grazing seasons of cow and calf grazing at 87.4% of the assesses stocking rate (table 2). The herbage production of domesticated grasses during 2011 was significantly greater than that produced during the other grazing seasons (table 9). Some of the increased domesticated grass herbage production was caused by precipitation at 169% of long-term mean during April, May, and July 2011 (table 1) and some of the increase resulted from low grazing pressure from steers stocked at 37.8% of the assessed stocking rate (table 2). Domesticated grass herbage production on pasture 3 was significantly less than that produced on nongrazed 4 during the 2007, 2008, and 2009 growing seasons and was significantly greater than that produced on pastures 1 & 2 during 2006, 2009, 2010, and 2011 growing seasons (tables 9 and 11). Mean basal cover of domesticated grass was 13.83% on pasture 3 that was not significantly different than that on nongrazed 4 and was significantly greater than that on pastures 1 & 2 (tables 9 and 11).

Native grass herbage production on pasture 3 was low with monthly biomass at less than 200 lbs/ac after the first year, 2006. Annual herbage biomass production of native grass on pasture 3 was not significantly different during all six growing seasons (tables 6 and 10). Native grass biomass production on pasture 3 was significantly less than that produced on nongrazed 4 during the 2007, 2009, and 2010 grazing seasons and was significantly less than that on pastures 1 & 2 during the 2007, 2008, 2009, 2010, and 2011 grazing seasons (tables 10 and 11). Mean basal cover of native grass was 0.18% on pasture 3 that was significantly less than those on nongrazed 4 and grazed pastures 1 & 2 (tables 10 and

11).

The mixed grass prairie study areas of grazed pastures 1 & 2 were degraded silty ecological sites dominated by Kentucky bluegrass. At the start of the study, the aboveground vegetation biomass consisted of 63.6% standing dead and litter and 36.4% live herbage. The live herbage biomass was 64.8% domesticated grasses and 3.4% native grasses. After 6 grazing seasons, the aboveground vegetation biomass consisted of 39.5% standing dead and litter and 60.5% live herbage. The live herbage biomass was 56.0% domesticated grasses and 27.0% native grasses.

Domesticated grass herbage biomass on pastures 1 & 2 progressively decreased during the first three grazing seasons as a result of the grazing pressure from cow-calf pairs. The low monthly domesticated grass biomass was less than 500 lbs/ac during the 2008 grazing season. Domesticated grass herbage production during the 2008, 2009, and 2010 grazing seasons was significantly less than that produced during the 2007 and 2011 grazing seasons (tables 7 and 9). Some of the increase in domesticated grass herbage production during 2011 was caused by high rainfall during April, May, and July 2011 (table 1) and some of the increase in domesticated grass resulted from the low stocking rates of grazing steers (table 2). Domesticated grass herbage biomass on pastures 1 & 2 was significantly less than that on nongrazed 4 during the six grazing seasons and was significantly less than that on pasture 3 during the 2006, 2009, 2010, and 2011 grazing seasons (tables 9 and 11). Mean basal cover of domesticated grass was 5.7% on pastures 1 & 2 that was significantly less than those on nongrazed 4 and grazed pasture 3 (tables 9 and 11).

Native grass herbage production on pastures 1 & 2 increased gradually during the six grazing seasons. Annual herbage biomass production of native grass on pastures 1 & 2 during the 2009 and 2011 grazing seasons was significantly greater than that produced during the 2006 and 2008 grazing seasons (tables 8 and 10). Native grass herbage production on pastures 1 & 2 was significantly greater than that produced on nongrazed 4 during the 2011 grazing season and was significantly greater than that produced on pasture 3 during the 2007, 2008, 2009, 2010, and 2011 grazing seasons (table 10). Mean basal cover of native grass was 6.62% on pastures 1 & 2 that was significantly greater than those on nongrazed 4 and pasture 3 (tables 10 and 11).

Rhizosphere weight (tables 12, 13, and 14) changed very little during the first two growing seasons and were not significantly different on nongrazed 4, pasture 3, and pastures 1 & 2. From the second growing season to the sixth growing season, the rhizosphere weights increased at different rates on the three management treatments resulting in significantly different mean annual rhizosphere weights on nongrazed 4 (table 12), pasture 3 (table 13), and pastures 1 & 2 (table 14).

Rhizosphere weight on nongrazed 4 increased 115.8% from a mean pregrazing rhizosphere weight of 60.49 kg/m^3 (14.9% of reference weight) at a mean rate of 13.2 kg/m^3/yr and after six growing seasons, the mean rhizosphere weight reached 130.56 kg/m^3 (table 12), which was 32.1% of the reference rhizosphere weight of 406.44 kg/m^3.

Rhizosphere weight on pasture 3 increased 176.2% from a mean pregrazing rhizosphere weight of 60.49 kg/m^3 at a mean rate of 23.8 kg/m^3/yr and after six grazing seasons, the mean rhizosphere weight reached 167.05 kg/m^3 (table 13), which was 41.1% of the reference rhizosphere weight of 406.44 kg/m^3.

Rhizosphere weight on pastures 1 & 2 increased 254.3% from a mean pregrazing rhizosphere weight of 60.49 kg/m^3 at a mean rate of 30.5 kg/m^3/yr and after six grazing seasons, the mean rhizosphere weight reached 214.34 kg/m^3 (table 14), which was 52.7% of the reference rhizosphere weight of 406.44 kg/m^3.

Mean annual rhizosphere weights on nongrazed 4 responded differently than those on grazed pasture 3 and on grazed pastures 1 & 2. The severely degraded silty ecological site on nongrazed 4 was dominated by Kentucky bluegrass and had no defoliation treatments. The changes in annual rhizosphere weights were related only to changes in growing season precipitation. The first growing season had low precipitation at 63.7% of the long-term mean and four growing season months (May, June, July, and August) had water deficiency conditions (table 1). The growing season precipitation during the second to the fourth growing seasons had mean precipitation at 76.2% of the long-term mean. Rhizosphere weight on nongrazed 4 changed little during the first four growing seasons. The precipitation increased during the fifth and sixth growing seasons at 103.4% of the long-term mean causing the rhizosphere weight to increase during the sixth growing season (table 12). The rhizosphere weight on nongrazed 4 increased 115.8% from a mean pregrazing rhizosphere weight of 60.49 kg/m^3 to 130.56 kg/m^3 in six years as a result of changes in annual growing season precipitation.

Mean annual rhizosphere weights on pasture 3 responded differently than that on nongrazed 4. The severely degraded silty ecological site on pasture 3 was dominated by smooth bromegrass and Kentucky bluegrass at a pretreatment composition of 93.9% and were partially defoliated annually by livestock grazing managed with the twice-over rotation system during six grazing seasons. Cow-calf pairs grazed during the first three years at a mean of 87.4% of the assessed stocking rate. Utilization of the smooth bromegrass herbage by the cows was around 36.4%. In three years, domesticated grass herbage biomass decreased 52.7% to 723.31 lbs/ac, standing dead biomass decreased 74.2% to 351.40 lbs/ac, litter biomass decreased 10.5% to 1883.70 lbs/ac, and native grass herbage biomass increased 64.7% to 57.60 lbs/ac. Heifers grazed during the next two years at a mean of 83.6% of the assessed stocking rate. Utilization of the smooth bromegrass herbage by the heifers was around 19.4%. In two years, standing dead biomass decreased 0.4% to 349.94 lbs/ac, litter biomass decreased 57.8% to 794.03 lbs/ac, domesticated grass herbage biomass increased 71.2% to 1238.61 lbs/ac, and native grass herbage biomass decreased 3.0% to 55.86 lbs/ac. Steers lightly grazed during the sixth year at 37.8% of the assessed stocking rate. Utilization of the smooth bromegrass herbage by the steers was around 6.1%. Domesticated grass herbage biomass increased 77.0% to 2191.98 lbs/ac, standing dead biomass decreased 26.8% to 256.28 lbs/ac, litter biomass increased 37.7% to 1093.64 lbs/ac, and native grass herbage biomass increased 52.4% to 85.12 lbs/ac.

The twice-over rotation grazing treatment on pasture 3 caused the rhizosphere weight to increase significantly greater than that on nongrazed 4. The increase of rhizosphere weight was not connected to changes in native grass. This increase was associated with the increase in Kentucky bluegrass basal cover. Native grass did not increase in herbage biomass and basal cover. The defoliation resistance mechanisms did not activate in native grass on pasture 3 most likely from deficiencies in the quantity of available fixed carbon. The grazing pressure did not remove sufficient quantities of standing smooth bromegrass that shaded the shorter native grasses and prevented the required rates of photosynthesis to occur causing the shortage of available carbon.

Smooth bromegrass is considered to be nonmycorrhizal and does not readily develop symbiotic relationships with rhizosphere organisms and cannot assist with increasing rhizosphere weight in an ecosystem. During another study, Manske (2007) recorded 32.3% of the root segments of smooth bromegrass from the control (no defoliation) treatment to be infected with endomycorrhizal fungi assessed by a present or absent grid-intersect method. However, nearly all of the fungal infections observed in the biologically active root segment samples were restricted to the root hairs. Almost none of the root segment samples had fungal colonization within the root tissue.

During six years of twice-over rotation grazing on pasture 3, basal cover of smooth bromegrass increased 63.3% and basal cover of Kentucky bluegrass increased 511.1%. The relative composition during the first year was 52.2% smooth bromegrass and 31.3% Kentucky bluegrass. As a result of the effects of grazing, the Kentucky bluegrass increased. The relative composition during the sixth year was 64.7% Kentucky bluegrass and 28.8% smooth bromegrass (table 15). Six years of livestock grazing on pasture 3 caused the relative composition of Kentucky bluegrass to increase 106.7% and the associated 176.2% increase in rhizosphere weight (table 15). The rhizosphere weight on pasture 3 was significantly greater during the third through the sixth years than the rhizosphere weight on nongrazed 4 (table 15).

Mean annual rhizosphere weights on pastures 1 & 2 responded differently that that on nongrazed 4. The severely degraded silty ecological sites on pastures 1 & 2 were dominated by Kentucky bluegrass and were partially defoliated annually by livestock grazing managed with the twice-over rotation system during six grazing seasons. Cow-calf pairs grazed during the first three years at a mean of 87.4% of the assessed stocking rate. In three years, domesticated grass herbage biomass decreased 70.9% to 310.77 lbs/ac, standing dead biomass decreased 65.9% to 420.37 lbs/ac, litter biomass decreased 32.9% to 1114.80 lbs/ac, and native grass herbage biomass increased 295.5% to 211.74 lbs/ac. Domesticated grass basal cover increased 18.3% to 4.08% and native grass basal cover increased 198.7% to 6.81%. Heifers grazed during the next two years at a mean of 83.6% of the assessed stocking rate. In two years, domesticated grass herbage biomass increased 120.7% to 685.72 lbs/ac, standing dead biomass decreased 13.5% to 363.68 lbs/ac, litter biomass decreased 57.5% to 473.94 lbs/ac, and native grass herbage biomass increased 63.8% to 346.76

lbs/ac. Domesticated grass basal cover increased 68.6% to 6.88% and native grass basal cover increased 12.5% to 7.66%. Steers lightly grazed during the sixth year at 37.8% of the assessed stocking rate. Domesticated grass herbage biomass increased 83.1% to 1261.24 lbs/ac, standing dead biomass increased 40.2% to 509.77 lbs/ac, litter biomass increased 89.5% to 898.17 lbs/ac, and native grass herbage biomass increased 63.5% to 567.07 lbs/ac. Domesticated grass basal cover remained the same at 6.88% and native grass basal cover decreased 15.7% to 6.46%.

The twice-over rotation grazing treatment for six years on pastures 1 & 2 caused the rhizosphere weight to increase significantly greater than that on nongrazed 4 (table 16 and figure 1). The increase of rhizosphere weight on pastures 1 & 2 was associated with the increase in native grass. The rhizosphere weights on pastures 1 & 2 were not significantly different than those on nongrazed 4 during the first two growing seasons. From the second growing season to the sixth growing season, the rate of rhizosphere weight increase was greater on pastures 1 & 2 than on nongrazed 4. The rhizosphere weights on pastures 1 & 2 were significantly greater than those on nongrazed 4 during each year from year three to year six (table 16 and figure 1). The rhizosphere weight on pastures 1 & 2 increased 254.3% from a mean pregrazing rhizosphere weight of 60.49 kg/m^2 to 214.34 kg/m^3 in six years in association with 183.3% increase in basal cover and 959.4% increase in herbage biomass of native grasses.

Domesticated grass biomass production was not significantly different on nongrazed 4 and pasture 3 during the 2013 and 2014 growing seasons. Domesticated grass biomass production on pastures 1 & 2 was significantly less than that produced on nongrazed 4 and pasture 3 during the 2013 and 2014 growing seasons (tables 17 and 18).

Domesticated grass biomass production on nongrazed 4 during the 2013 and 2014 growing seasons was not significantly different than that produced during 2006, 2007, 2009, 2010, and 2011 growing seasons and was significantly greater than that produced during the 2008 growing season (tables 3, 9, 11, 17, and 18). Domesticated grass biomass production on pasture 3 during the 2013 and 2014 grazing seasons was not significantly different than that produced during 2011 grazing season and was significantly greater than that produced during the 2006 to 2010 grazing seasons (tables 5, 9, 11, 17, and 18). Domesticated grass biomass production on pastures 1 & 2 during the 2013 and 2014 grazing seasons was significantly greater than that produced during the 2008 and 2009 grazing seasons but not significantly different than that produced during the 2006, 2007, 2010 and 2011 grazing seasons (tables 7, 9, 11, 17, and 18). Domesticated grass basal cover during 2013 and 2014 on nongrazed 4 and pasture 3 was significantly greater than that on the respective treatments during 2006 to 2011 (tables 9, 11, and 18). Domesticated grass basal cover during 2013 and 2014 on pastures 1 & 2 was not significantly different than that during 2006 and 2011 (tables 9, 11, and 18).

Native grass biomass production on pastures 1 & 2 was significantly greater than that on pasture 3 during the 2013 and 2014 grazing seasons. Native grass biomass production was not significantly different on nongrazed 4 and pasture 3 during the 2013 and 2014 growing seasons (tables 17 and 18).

Native grass biomass production on nongrazed 4 during the 2013 and 2014 growing seasons was not significantly different than that produced during the 2006 to 2011 growing seasons (tables 4, 10, 11, 17, and 18). Native grass biomass production on pasture 3 during the 2013 and 2014 grazing seasons was not significantly different than that produced during the 2006 to 2011 grazing seasons (tables 6, 10, 11, 17, and 18). Native grass biomass production on pastures 1 & 2 during the 2013 and 2014 grazing seasons was not significantly different than that produced during the 2006 to 2011 grazing seasons (tables 8, 10, 11, 17, and 18). Native grass basal cover during 2013 and 2014 on nongrazed 4, pasture 3, and pastures 1 & 2 was not significantly different than that on the respective treatments during 2006 to 2011 (tables 10, 11, and 18).

The quantity of mineral nitrogen available in a soil is the net difference between the total quantity of organic nitrogen mineralized by soil microorganisms and the quantity of mineral nitrogen immobilized by plants and soil microbes (Brady 1974, Legg 1975). The quantity of available mineral nitrogen varies cyclically with changes in soil temperature, soil microorganism biomass, and plant phenological growth and development during the growing season (Whitman 1975). The relationships between soil microorganism activity and phenology of plant growth activity results in a dynamic cycle of available mineral nitrogen (Goetz 1975). When mineralization activity by soil microbes is greater than plant growth activity, the quantity of available mineral nitrogen increases. When transformation (immobilization) of mineral nitrogen by plant and soil microbe growth activity is greater than mineralization activity, the quantity of available mineral nitrogen decreases.

The available mineral nitrogen cycle model for a typical growing season would have three peaks and three valleys (Whitman 1975). The first peak of mineral nitrogen would occur in mid May. As plant growth rates increased in June, transformation would increase with available mineral nitrogen at a low value during late June-early July. Mineral nitrogen would increase and reach a second peak during late July or early August. Fall tillers and fall tiller buds start development in mid August and would cause a decrease in available mineral nitrogen until mid October. A third peak would occur shortly after mid October. And when liquid water becomes unavailable with winter soil freeze up, available mineral nitrogen would decline for a third low period.

Nitrate (NO_3) cycle on nongrazed 4 had minor peaks during May at the 0-6 and 6-12 inch soil depths (table 19). Generally, available mineral nitrate was low and transformation was low during the growing season at the 0-6 and 6-12 inch soil depths. At the 12-24 inch soil depth, mineral nitrate accumulated during June, July, and August. There was a slight decrease in available mineral nitrate and a slight increase in transformation during August and September at the 0-6 inch soil depth. There was a slight increase in available mineral nitrate and a slight decrease in transformation during July and again during October at the 0-6 inch soil depth (table 19).

Ammonium (NH_4) cycle on nongrazed 4 had a peak during May at the 0-6 inch soil depth and a minor peak at the 6-12 inch soil depth (table 19). Generally, available mineral ammonium was moderate during the growing season at all soil depths and transformation was moderate at the 0-6 inch soil depths, low at the 6-12 inch soil depth, and ammonium accumulated at the 12-24 inch soil depth. There was a slight decrease in available mineral ammonium and a slight increase in transformation during August at the 0-6 inch soil depth. There was a slight increase in available mineral ammonium and a slight decrease in transformation during July at the 0-6 inch soil depth (table 19).

Nitrate (NO_3) cycle on pasture 3 had a peak during May at the 0-6 inch soil depth (table 20). Generally, available mineral nitrate was low and transformation was low during the growing season at all soil depths. Except transformation was at a moderate level during July to October at the 0-6 inch soil depth. There was a slight decrease in available mineral nitrate and a slight increase in transformation during August and again during October at the 0-6, 6-12, and 12-24 inch soil depths. There was a slight increase in available mineral nitrate and a slight decrease in transformation during July and again during September at the 0-24 inch soil depth (table 20).

Ammonium (NH_4) cycle on pasture 3 was delayed. The available mineral ammonium was greater during June than during May at the 0-6, 6-12, and 12-24 inch soil depths (table 20). There was a slight decrease in available mineral ammonium and a slight increase in transformation during July and August and again during October at the 0-6, 6-12, and 12-24 inch soil depths. There was a slight increase in available mineral ammonium and a great enough decrease in transformation to cause ammonium accumulation during September at the 0-24 inch soil depth (table 20).

Nitrate (NO_3) cycle on pastures 1 & 2 had a peak during May at the 0-6, 6-12, and 12-24 inch soil depths (table 21). Generally, available mineral nitrate was high and transformation was high during June through October at the 0-6, 6-12, and 12-24 inch soil depths. There was a slight increase in available mineral nitrate and a slight decrease in transformation during August at the 0-6 and 12-24 inch soil depths. There was a slight decrease in available mineral nitrate and a slight increase in transformation during July and again during September and October at the 0-6 and 12-24 inch soil depths (table 21).

Ammonium (NH_4) cycle on pastures 1 & 2 had a peak during May at the 0-6 inch soil depth and had minor increases at the 6-12 and 12-24 inch soil depths (table 21). Generally, available mineral ammonium was high and transformation was high during the growing season at all soil depths. There was a trend in the 0-24 inch soil column for a slight increase in available mineral ammonium and a slight decrease in transformation during July, August, and September. There was a slight decrease in available mineral ammonium and a slight increase in transformation during June and again in October at the 0-24 inch soil depth (table 21).

Available mineral nitrogen ($NO_3 + NH_4$) on nongrazed 4 was 15.8% greater than that on pasture 3. However, transformed mineral nitrogen on pasture 3 was 16.5% greater than that used on nongrazed 4. Mineral nitrogen use on nongrazed 4 was primarily from the 0 to 12 inch soil depths. Both nitrate (NO_3) and ammonium (NH_4) tended to accumulate at the 12 to 24 inch soil depths on nongrazed 4 (table 22).

Available mineral nitrogen (NO_3 + NH_4) on pastures 1 & 2 was 8.9% greater than that on nongrazed 4 and was 26.1% greater than that on pasture 3. Transformed mineral nitrogen on pastures 1 & 2 was 234.3% greater than that used on nongrazed 4 and was 187.0% greater than that used on pasture 3 (table 22).

Available mineral nitrogen (NO_3 + NH_4) during May was lowest on pasture 3. Pasture 3 was dominated by smooth bromegrass and nongrazed 4 and pastures 1 & 2 were dominated by Kentucky bluegrass. Available mineral nitrogen on nongrazed 4 during May was 10.5% greater than that on pasture 3. Nitrate (NO_3) was 8.4% greater and ammonium (NH_4) was 12.2% greater on nongrazed 4 during May than that on pasture 3 (table 23).

Available mineral nitrogen (NO_3 + NH_4) during May was greatest on pastures 1 & 2. Both nitrate and ammonium was available during May at greater quantities at each soil depth on pastures 1 & 2 than those on nongrazed 4 and pasture 3. Available mineral nitrogen on pastures 1 & 2 during May was 39.5% greater than that on nongrazed 4 and was 54.2% greater than that on pasture 3. Pastures 1 & 2 were the only treatment that had mineral nitrogen available at quantities near 100 lbs/ac (table 23).

Summary of Results

The first four growing seasons of the study received precipitation that was 73.1% of the long-term mean. During the fifth and sixth years, growing season precipitation was 103.4% of the long-term mean. Nongrazed 4 had no defoliation treatment during the study. Pasture 3 and pastures 1 & 2 had partial defoliation by grazing treatment that was controlled by the twice-over rotation strategy. Cow-calf pairs grazed during the first three years at a mean of 87.4% of the assessed stocking rate, heifers grazed during the fourth and fifth years at a mean of 83.6% of the assessed stocking rate, and steers grazed during the sixth year at 37.8% of the assessed stocking rate.

The nongrazed 4 plant communities on the degraded silty ecological site was dominated by Kentucky bluegrass. Mean annual domesticated grass herbage biomass was 1847.69 lbs/ac that changed little. There was a 24.8% decrease and a 17.0% decrease during the third and fifth growing seasons, respectively, and a 39.1% increase during the sixth growing season. Mean annual domesticated grass basal cover was 12.97% that had small annual changes. These changes to the domesticated grasses were related to changes in the precipitation pattern. Mean annual native grass herbage biomass was 240.42 lbs/ac and mean annual basal cover was 1.46%. There was a small quantity of native grasses remaining on nongrazed 4 and most of the native grass was a small remnant colony of prairie sandreed that was able to persist because it was taller than the Kentucky bluegrass.

The pasture 3 plant community on the degraded silty ecological site was dominated by smooth bromegrass and Kentucky bluegrass. Mean annual domesticated grass herbage biomass was 1434.37 lbs/ac. There was a 49.1% decrease during the first three grazing seasons. Increased herbage was produced during the fourth and fifth grazing seasons with an 85.2% increase during the sixth grazing season. Mean annual domesticated grass basal cover was 13.83%. Basal cover increased during the second to the fifth grazing season at a mean of 25.4% per year. During the six year period, smooth bromegrass basal cover increased 63.3% and composition decreased from 52.2% to 28.8%; Kentucky bluegrass basal cover increased 511.1% and composition increased from 31.3% to 64.7%. These changes to the domesticated grasses were related to changes in the precipitation pattern and to changes in the grazing pressure. Mean annual native grass herbage biomass was 80.92 lbs/ac and mean annual basal cover was 0.18%. There was an extremely small quantity of native grasses remaining on pasture 3. Livestock utilization of the smooth bromegrass vegetation was too low to help the native grasses. Cow-calf pairs grazed three seasons at a mean of 87.4% of assessed stocking rate and utilized 36.4% of the smooth bromegrass; heifers grazed two seasons at a mean of 83.6% of the assessed stocking rate and utilized 19.4% of the smooth bromegrass; and steers grazed one season at 37.8% of the assessed stocking rate and utilized 6.1% of the smooth bromegrass.

The pastures 1 & 2 plant communities on the degraded silty ecological sites were dominated by Kentucky bluegrass. Mean annual domesticated grass herbage biomass was 847.25 lbs/ac. The three grazing seasons of cow-calf grazing at a mean of 87.4% of the assessed stocking rate reduced the domesticated herbage biomass 65.6%. The two grazing seasons of heifer grazing at a mean of 83.6% of the assessed stocking rate maintained the domesticated herbage at relatively low weight levels with only slight increases. The one grazing season of steers grazing at 37.8% of the assessed stocking rate plus above average precipitation during April, May, July, and August of the sixth grazing season permitted domesticated herbage to increase 85.5% during one growing season. Mean annual domesticated grass basal cover was 5.70%. The basal cover increased 2 percentage points during six grazing seasons. The reductions in the domesticated grass vegetation were related to the grazing strategy. Mean annual native grass herbage biomass was 377.91 lbs/ac. The native grass herbage biomass generally increased with a six year increase of 166.3%. Mean annual native grass basal cover was 6.62%. Native grass basal cover had a six year increase of 152.9%. The increases in the native grass vegetation were related to the grazing strategy.

Rhizosphere weight on nongrazed 4 increased 115.9% at a mean rate of 13.2 kg/m^3/yr, with 50.3% of that increase occurring during the sixth growing season, from 14.9% to 32.1% of the reference rhizosphere weight. The small increase in rhizosphere weight on nongrazed 4 were related to the increase in precipitation during the fifth and sixth growing seasons.

Rhizosphere weight on pasture 3 increased 176.2% at a mean rate of 23.8 kg/m^3/yr from 14.9% to 41.1% of the reference rhizosphere weight. The increase in rhizosphere weight on pasture 3 was related to the increase in Kentucky bluegrass composition from 31.3% to 64.7% and the decrease in smooth bromegrass composition from 52.2% to 28.8% that was caused by the grazing management. Smooth bromegrass does not develop symbiotic relationships with rhizosphere microorganism and Kentucky bluegrass can live with or without the symbiotic soil microbes. On pasture 3, the rhizosphere microbes developed in association with Kentucky bluegrass roots.

Rhizosphere weight on pastures 1 & 2 increased 254.3% at a mean rate of 30.5 kg/m^3/yr from 14.9% to 52.7% of the reference rhizosphere weight. The increase in rhizosphere weight on pastures 1 & 2 was related to the increase in native grasses, the decrease in domesticated grasses, and the increase in ecosystem biogeochemical processes caused by the twice-over rotation strategy.

Available mineral nitrate during May and during the growing season was greatest on pastures 1 & 2. Available mineral nitrate on pastures 1 & 2 during May was 78.3% greater than that on pasture 3 and was 64.6% greater than that on nongrazed 4. During the growing season, available mineral nitrate on pastures 1 & 2 was 33.1% greater than that on pasture 3 and was 5.2% greater than that on nongrazed 4. During May, available mineral nitrate on nongrazed 4 was 8.4% greater than that on pasture 3, and during the growing season, available mineral nitrate on nongrazed 4 was 26.5% greater than that on pasture 3. Transformation of mineral nitrate was greatest on pastures 1 & 2. Transformation of mineral nitrate on pastures 1 & 2 was 173.7% greater than that used on pasture 3 and was 291.2% greater than that used on nongrazed 4. Transformation of mineral nitrate on pasture 3 was 42.9% greater than that used on nonrgazed 4.

Available mineral ammonium during May and during the growing season was greatest on pastures 1 & 2. Available mineral ammonium on pastures 1 & 2 during May was 35.2% greater than that on pasture 3 and was 20.5% greater than that on nongrazed 4. During the growing season, available mineral ammonium on pastures 1 & 2 was 22.1% greater than that on pasture 3 and was 11.3% greater than that on nongrazed 4. During May, available mineral ammonium on nongrazed 4 was 12.2% greater than that on pasture 3 and during the growing season, available mineral ammonium on nongrazed 4 was 9.7% greater than that on pasture 3. Transformation of mineral ammonium was greatest on pastures 1 & 2. Transformation of mineral ammonium on pastures 1 & 2 was 241.7% greater than that used on pasture 3 and was 124.1% greater than that used on nongrazed 4. Transformation of mineral ammonium on nongrazed 4 was 52.5% greater than that used on pasture 3.

Discussion

Native grassland ecosystems are complex and consist of numerous interrelated essential components. The major biotic components are the grassland plants, the grazing graminivores, and the rhizosphere microorganisms. The abiotic components are sunlight energy, the major essential elements of carbon, hydrogen, nitrogen, and oxygen, the minor essential elements of macronutrients and micronutrients, and the environmental factors.

Traditional management of grasslands is based on the use of the aboveground grass plants as forage for livestock. The belowground rhizosphere microorganisms that cycle the essential elements and are the renewable portion of natural resources are not considered in traditional management. Sometimes the use priority changes from forage for livestock to recreation and/or wildlife habitat. The graminivores are than considered to be a competing use and are removed. The symbiotic relationships among the three main biotic components and the cycling of essential elements are destroyed without the presence of graminivores.

Grass plants produce double the leaf biomass than that needed for growth and development (Crider 1955, Coyne et al. 1995). The extra plant biomass provides nutrious forage to graminivores and acts as an enticement for partial defoliation when the lead tillers are at vegetative growth stages that forces the exudation of large quantities of short chain carbon energy into the rhizosphere. This exudated energy causes the biomass of the microbes to increase that results in greater mineralization of organic nitrogen. Removal of the graminivores effectually turns the previously beneficial extra leaf biomass into detrimental shade producing vestiges and prevents the exudation of carbon energy into the rhizosphere. With the reduction of carbon energy exudates, the rhizosphere microbes decrease in biomass resulting in a reduction in organic nitrogen mineralization. The decrease in available mineral nitrogen causes a great reduction of native grass leaf and root growth and a reduction in vegetative tiller development to less than one secondary tiller per lead tiller.

Prior to the decision to eliminate the competitive usage of resources by grazing graminivores, the area was a working cattle ranch that was managed with traditional concepts supported by good land stewardship ethics and the land most likely was in a typical low good condition with mineral nitrogen available at 50 to 60 lbs/ac and with the biomass of the rhizosphere microorganisms at 50% to 60% of the biomass needed to mineralize 100 lbs/ac of mineral nitrogen. The native grassland ecosystems deteriorated rapidly after grazing graminivores were eliminated. The rhizosphere microorganism biomass would decrease greatly during the first two growing seasons then continue to decrease at a slower rate for another year or two. Rhizosphere biomass can be sustained by the leakage of carbon energy from a grass plant at a low weight at about 14.9% of the rhizosphere biomass required to mineralize 100 lbs/ac of mineral nitrogen.

Analytically, the primary initial cause for the native grassland ecosystem degradation after the graminivores were removed would be the huge reduction in the quantity of available mineral nitrogen. The reduction in mineral nitrogen causes great decreases in native grass herbage production and decreases in basal cover which creates open bare ground spots in the plant community.

Opportunistic plants like smooth bromegrass and Kentucky bluegrass invade and rapidly fill the open spaces. Kentucky bluegrass expansion is limited in the area that the taller smooth bromegrass has invaded. Both smooth bromegrass and Kentucky bluegrass have labile roots that rapidly breakdown after death providing the essential elements back to the plants to produce new growth of leaves, stems, and roots. Within a few years, the greater aboveground growth of the invading domesticated cool season grasses dominate the plant communities and shade access of sunlight energy to the remaining stunted native grasses that have impeded growth as a result of great deficiencies in the essential elements of nitrogen, carbon, hydrogen, and oxygen.

After 13 years without grazing graminivores, the aboveground vegetative biomass on the degraded plant communities consisted of 40.0% litter, 27.4% standing dead, and 32.6% live herbage. The live herbage biomass was 79.9% domesticated grasses, 2.7% native grasses, 11.9% upland sedge, and 5.5% forbs. The mean rhizosphere biomass was reduced to 60.49 kg/m^3 which was only 14.9% of the reference rhizosphere weight.

The severely degraded silty ecological sites on pastures 1 & 2 were partially restored by grazing management with the twice-over rotation strategy during a nine year period 2006 to 2014. Composition of the invader domesticated grass, Kentucky bluegrass, decreased 50.9% on pastures 1 & 2 as a result of the grazing treatment. Kentucky bluegrass composition was 64.8% in 2006, decreased to 56.0% in 2011, and decreased to 31.8% during 2013 to 2014. Kentucky bluegrass herbage biomass decreased 51.8% to a mean low of 537.14 lbs/ac during the three year period, 2008 to 2010. Composition of native grass (cool and warm season grasses) increased 641.2% on pastures 1 & 2 as a result of the grazing treatment. Native grass composition was 3.4% in 2006, increased to 27.0% in 2011, and was at 25.2% during 2013 to 2014. Native grass herbage biomass increased 166.3% to a mean high at 616.43 lbs/ac during 2011. The rhizosphere weight increased 254.3% on pastures 1 & 2 at a mean rate of 30.5 kg/m^3/yr to a mean high during 2011 at 214.34 kg/m^3, which was 52.7% of the reference rhizosphere weight. Available mineral nitrogen on pastures 1 & 2 was the greatest during 2013 to 2014 at 99.35 lbs/ac; almost at the threshold quantity of 100 lbs/ac. Available mineral nitrogen on pastures 1 & 2 was 39.5% greater than that on nongrazed 4 and 54.2% greater than that on pasture 3. The grassland ecosystems on pastures 1 & 2 can be further restored with a rhizosphere biomass near the reference weight of 406.44 kg/m^3, and mineral nitrogen available at quantities greater than 100 lbs/ac and the plant communities can be restored with a dominance of native grasses and negligible amounts of Kentucky bluegrass with continuance of stocking rates between 85% and 100% of the assessed rate and management of grazing with the twice-over rotation strategy.

The native grassland ecosystems on pasture 3 were not restored with the twice-over treatment because the inhibitive shading effects from the live and standing dead smooth bromegrass was not reduced sufficiently with defoliation by grazing at stocking rates of less than 85% of the assessed rate with yearling heifer and steer stocker livestock. Shading of sunlight energy impeded native grass growth. Native grass monthly herbage biomass remained low at less than 200 lbs/ac during the second to the sixth growing seasons and the mean basal cover of native grass was only 0.18% on pasture 3.

Light energy from the sun is necessary for photosynthesis. Light penetration through a tall grass leaf canopy can be about 20% of the light levels above the canopy (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 and survive in low light conditions.

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

Severely degraded native grassland ecosystems can not be restored rapidly. The rhizosphere microorganism biomass must be restored before the native grass species composition can be recovered. The restoration of the ecosystem can progress at the rate of rhizosphere restoration. Rhizosphere restoration requires increasing the quantity of short chain carbon energy exudation from partially defoliated lead tillers of host grass species that form symbiotic relations with rhizosphere organisms and that retain 67% to 75% of their live leaf biomass for active carbon fixation during vegetative growth stages. Mowing at hay cutting height or burning removes too much leaf biomass for the host grass species to increase rhizosphere microbe biomass with surplus short chain carbon energy.

Smooth bromegrass was domesticated several centuries ago and does not form effective symbiotic relations with rhizosphere microbes. Because smooth bromegrass is not a host species, fifty percent of its leaf biomass can be removed by grazing during vegetative growth stages to reduce the detrimental shading effects on the growth of small understory native grass plants. However, if too much of the shading material is removed early in the restoration process, the increased sunlight reaching the ground will activate seeds of weedy plants to grow, turning restoration backwards and lengthening the recovery time.

The rhizosphere weight increased 176.2% on pasture 3 at a mean rate 23.8 kg/m^3/yr to a mean high during 2011 at 167.05 kg/m^3, which was 41.1% of the reference rhizosphere weight. Available mineral nitrogen on pasture 3 was the lowest during 2013 to 2014 at 64.45 lbs/ac. Available mineral nitrogen on pasture 3 was 9.5% lower than that on nongrazed 4 and 35.1% lower than that on pastures 1 & 2. Domesticated grass herbage biomass and basal cover on pasture 3 was not different than that on nongrazed 4 during 2010 to 2011 and 2013 to 2014. The composition of the domesticated grass shifted from 52.2% smooth bromegrass and 31.3% Kentucky bluegrass to 64.7% Kentucky bluegrass and 28.8% smooth bromegrass in six grazing seasons.

Native grass herbage biomass was barely present at 77.37 lbs/ac during 2010 to 2011 and at 56.50 lbs/ac during 2013 to 2014. These data indicate that native grasses on pasture 3 were impeded by deficiencies in available nitrogen and carbon and that rhizosphere microorganisms with biomass at less the 50% of the reference rhizosphere biomass are not great enough to restore native grassland ecosystems. Even though the ecosystems on pasture 3 are a long way from being restored, some progress was made. The rhizosphere biomass had increased and was 28.0% greater than that on nongrazed 4. The composition of smooth bromegrass was reduced 44.8%. The shading problem caused by live and standing dead smooth bromegrass must be reduced in order for the native grass leaves to fix sufficient quantities of carbon. After the rhizosphere biomass increases above 50% of the reference rhizosphere weight, the available mineral nitrogen will increase and then the native grass species will increase and eventually outcompete the Kentucky bluegrass as was done on pastures 1 & 2.

Degradation of native grassland ecosystems occurs when the available mineral nitrogen (NO_3 nitrate and NH_4 ammonium) drops below 100 lbs/ac. However, native grassland soils are not deficient of nitrogen. Most of the nitrogen is immobilized in the soils as organic nitrogen. Grassland soils in the Northern Plains contains organic nitrogen at a range of 3 to 8 tons per acre. Organic nitrogen is not usable by plants. Soil organic nitrogen must be converted into mineral nitrogen through mineralization by soil microorganisms. In grasslands, almost all of the soil microorganisms live in the rhizosphere around living active perennial grass roots. The quantity of the rhizosphere microorganism biomass determines the quantity of organic nitrogen mineralized into mineral nitrogen. Mineral nitrogen available at quantities of 100 lbs/ac or greater are needed to produce herbage biomass and calf weight gain per acre at ecosystems biological potential levels (Wight and Black 1972). Native grassland ecosystems are deficient in mineral nitrogen when it is not available at quantities of 100 lbs/ac and those grassland ecosystems degrade down to the level of available mineral nitrogen. Most traditional grazing practices are based on the use of the aboveground grass herbage biomass as forage for livestock and typically have available mineral nitrogen at 50 to 70 lbs/ac because these practices are supported by good land stewardship ethics. When livestock are removed from the grassland ecosystem, the degradation is severe and the rhizosphere biomass decreases to less than 15% of the reference rhizosphere biomass.

Restoration of degraded native grassland ecosystems requires the elevation of the rhizosphere microorganism biomass. The primary producer trophic level in the rhizosphere are achlorophyllous saprophytes and they can not fix carbon energy. Growth and development of all rhizosphere microorganisms is limited by access of short chain carbon energy (Manske 2011, 2014).

Healthy grass plants fix greater quantities of atmospheric carbon during photosynthesis than the plant needs for growth and development (Coyne et al. 1995). Some of this surplus short chain carbon energy can be moved from the grass tiller by exudation through the roots into the rhizosphere with partial defoliation by large grazing graminivores that remove 25% to 33% of the aboveground leaf weight while the lead tiller is at vegetative phenological growth stages between the three and a half new leaf stage and the flower stage. This growth stage occurs for 45 days each year from 1 June to 15 July for cool and warm season native grasses (Manske 1999, 2011, 2014).

The quantity of available mineral nitrogen below 100 lbs/ac determines the degree of grassland ecosystem degradation. The biomass of the rhizosphere microorganisms determines the quantity of soil organic nitrogen converted into mineral nitrogen by mineralization. Grassland ecosystems that are deficient in mineral nitrogen below 100 lbs/ac are low in rhizosphere microorganism biomass and the rhizosphere microorganisms are deficient in short chain carbon energy. The solution is to implement a twice-over rotation grazing strategy that activates the existing physiological mechanisms and biogeochemical processes of the native grassland ecosystems. The cattle partially defoliate grass lead tillers at vegetative growth stages that moves surplus carbon energy from the grass plants to the rhizosphere microorganisms that increase in biomass. The greater biomass of rhizosphere microorganisms convert greater quantities of organic nitrogen into mineral nitrogen. Mineral nitrogen available at quantities of 100 lbs/ac or greater produce greater herbage biomass at high quality. The cows milk at their genetic potential for most of the grazing season and their calves gain weight at their genetic potential producing greater calf weight per acre.

Acknowledgment

I am grateful to Sheri Schneider for assistance in production of this manuscript and for development of the tables and figure.

Table 1. Precipitation in inches for growing season months for 2006-2011, Richardton, North Dakota.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season
Long-term mean (1971-2000)	1.75	2.49	3.39	2.27	1.88	1.60	1.41	14.79
2006	2.53	0.60	0.37	0.79	1.40	2.33	1.40	9.42
% of LTM	144.57	24.10	10.91	34.80	74.47	145.63	99.29	63.69
2007	1.04	3.57	2.22	0.44	1.57	1.29	0.62	10.75
% of LTM	59.43	143.37	65.49	19.38	83.51	80.63	43.97	72.68
2008	0.45	1.32	3.93	2.04	0.56	1.70	1.45	11.45
% of LTM	25.71	53.01	115.93	89.87	29.79	106.25	102.84	77.42
2009	0.59	0.85	3.09	2.82	0.53	1.67	2.08	11.63
% of LTM	33.71	34.14	91.15	124.23	28.19	104.38	147.52	78.63
2010	0.71	3.29	4.35	1.42	0.90	2.30	0.46	13.43
% of LTM	40.57	132.13	128.32	62.56	47.87	143.75	32.62	90.80
2011	2.01	4.94	1.76	4.06	2.07	0.96	1.35	17.15
% of LTM	114.86	198.39	51.92	178.85	110.11	60.00	95.74	115.96
2006-2011	1.22	2.43	2.62	1.93	1.17	1.71	1.23	12.31
% of LTM	69.71	97.59	77.28	85.02	62.23	106.88	87.23	83.23

Table 2. Animal Unit Equivalent, Herd Weight, and Stocking Rate used 2006 to 2011 compared to 2011 assessed values on Schnell Recreation Area.

	Animal Units		Herd Weight		Stocking Rate	
	Used	2011 Assessed	Used	2011 Assessed	Used	2011 Assessed
	AUE	175.53		175533		1.92
Year	#	%	lbs	%	ac/AUM	%
2006	113.82	64.84	126114	71.85	2.66	72.30
2007	132.56	75.52	144462	82.30	2.33	82.55
2008	171.51	97.71	188095	107.16	1.79	107.46
2009	145.74	83.03	139332	79.38	2.41	79.80
2010	154.90	88.25	152561	86.91	2.20	87.42
2011	73.45	41.84	66005	37.60	5.09	37.80

Table 3. Mean aboveground herbage production for domesticated grass in lbs/ac during the growing season on the silty ecological sites of nongrazed 4 on the Schnell Recreation Area, 2006-2011.

Domesticated Grass	30 May	15 Jun	30 Jun	15 Jul	15 Aug	15 Sep	15 Oct
2006	1684.81	1951.70	2071.58	1782.57	1676.96	1639.85	2029.48
2007	1489.28	1741.90	1772.40	1760.81	1742.97	1955.26	2076.58
2008	901.99	1296.61	1211.69	1394.37	1490.00	1476.44	1470.02
2009	1111.79	1868.92	1554.93	1711.21	1871.77	2201.46	2137.23
2010	1076.82	1106.79	1462.17	1532.81	1370.83	1609.17	2122.25
2011	911.98	1615.59	1894.61	2096.56	3109.87	3120.57	3588.69
Mean	1196.11	1596.92	1661.23	1713.06	1877.07	2000.46	2237.38

Table 4. Mean aboveground herbage production for native grass in lbs/ac during the growing season on the silty ecological sites of nongrazed 4 on the Schnell Recreation Area, 2006-2011.

Native Grass	30 May	15 Jun	30 Jun	15 Jul	15 Aug	15 Sep	15 Oct
2006	36.39	104.90	42.82	217.65	156.28	294.00	74.22
2007	2.14	313.98	434.41	386.24	303.28	126.66	90.98
2008	94.91	86.70	194.81	254.05	168.40	165.55	32.83
2009	111.32	291.15	401.75	427.44	439.58	234.06	229.06
2010	175.55	260.47	497.38	287.58	226.21	361.80	176.97
2011	104.89	219.07	249.76	344.67	490.24	10.00	59.94
Mean	87.53	212.71	303.49	319.61	297.33	198.68	110.67

Table 5. Mean aboveground herbage production for domesticated grass in lbs/ac during the growing season on the silty ecological sites of pasture 3 on the Schnell Recreation Area, 2006-2011.

Domesticated Grass	30 May	15 Jun	30 Jun	15 Jul	15 Aug	15 Sep	15 Oct
2006	1529.96	1634.14	1460.74	1241.66	1158.17	1620.59	1771.87
2007	1089.67	1767.94	1596.32	1424.35	1341.57	1111.08	759.98
2008	536.63	1299.61	923.40	785.67	598.00	439.58	480.25
2009	1014.74	1183.15	1587.05	1437.19	1460.74	1502.13	1382.96
2010	1009.74	1345.14	1569.21	1538.52	1126.06	1081.10	1000.47
2011	1155.32	1972.39	2312.06	2156.50	2931.47	2425.53	2390.56
Mean	1056.01	1533.73	1574.80	1430.65	1436.00	1363.34	1297.68

Table 6. Mean aboveground herbage production for native grass in lbs/ac during the growing season on the silty ecological sites of pasture 3 on the Schnell Recreation Area, 2006-2011.

Native Grass	30 May	15 Jun	30 Jun	15 Jul	15 Aug	15 Sep	15 Oct
2006	34.97	72.07	88.49	227.64	89.91	282.58	57.08
2007	9.99	0.89	18.55	135.58	71.36	34.97	33.54
2008	34.97	78.50	37.10	96.34	120.60	24.26	11.42
2009	14.28	92.77	112.04	186.25	44.24	59.23	9.28
2010	18.56	33.54	127.73	137.01	7.13	32.11	34.96
2011	39.96	58.51	73.50	183.40	158.42	8.56	73.50
Mean	25.46	56.05	76.24	161.04	81.94	73.62	36.63

Table 7. Mean aboveground herbage production for domesticated grass in lbs/ac during the growing season on the silty ecological sites of pastures 1 and 2 on the Schnell Recreation Area, 2006-2011.

Domesticated	30	15	30	15	15	15	15

Grass	May	Jun	Jun	Jul	Aug	Sep	Oct
2006	1066.48	1114.64	898.78	738.58	803.52	832.06	1228.82
2007	823.32	1197.42	1238.10	1347.01	1196.62	1204.20	1085.86
2008	241.56	489.53	333.61	427.09	159.14	387.84	136.66
2009	382.13	530.21	665.43	705.75	606.92	411.04	531.63
2010	516.29	613.34	839.55	661.51	704.32	718.24	746.79
2011	882.01	1226.68	943.38	1226.32	1396.16	1583.13	1570.99
Mean	651.97	861.97	819.81	851.04	811.11	856.09	883.46

Table 8. Mean aboveground herbage production for domesticated grass in lbs/ac during the growing season on the silty ecological sites of pastures 1 and 2 on the Schnell Recreation Area, 2006-2011.

Native Grass	30 May	15 Jun	30 Jun	15 Jul	15 Aug	15 Sep	15 Oct
2006	53.53	234.06	228.71	296.50	225.15	218.72	185.90
2007	131.57	258.06	573.73	308.73	583.82	351.90	188.96
2008	200.52	199.46	293.29	259.04	260.47	181.97	87.42
2009	265.46	406.40	399.26	591.94	689.34	357.16	400.33
2010	301.50	269.75	563.39	474.19	223.71	322.19	272.60
2011	270.81	569.10	810.29	564.82	675.78	628.32	450.28
Mean	203.90	322.81	478.11	415.87	443.05	343.38	264.25

Table 9. Mean annual domesticated grass herbage biomass (lbs/ac) and basal cover (%) on the silty ecological sites of three treatments on the Schnell Recreation Area, 2006-2011.

Management Treatment	2006	2007	2008	2009	2010	2011
Nongrazed 4						
Domesticated Herbage	1858.69ax	1841.65ax	1389.86ay	1840.92ax	1534.00axy	2570.98ax
Basal Cover	10.55	17.30	12.55	6.75	17.45	13.20
Pasture 3						
Domesticated Herbage	1481.20ay	1333.54byz	754.42bz	1425.24by	1276.75ayz	2364.75ax
Basal Cover	4.80	10.75	12.55	17.30	21.65	15.90
Pastures 1 & 2						
Domesticated Herbage	936.07bx	1211.54bx	322.31bz	575.16cy	713.96by	1324.44bx
Basal Cover	4.80	5.35	4.08	6.20	6.88	6.88

Means in the same column and followed by the same letter (a, b, c) are not significantly different ($P<0.05$).
Means in the same row and followed by the same letter (x, y, z) are not significantly different ($P<0.05$).

Table 10. Mean annual native grass herbage biomass (lbs/ac) and basal cover (%) on the silty ecological sites of three treatments on the Schnell Recreation Area, 2006-2011.

Management Treatment	2006	2007	2008	2009	2010	2011
Nongrazed 4						
Native Grass Herbage	148.31axy	275.93axy	150.39aby	337.17ax	301.14axy	228.95axy
Basal Cover	1.25	1.50	2.20	0.85	2.20	0.75
Pasture 3						
Native Grass Herbage	136.30ax	49.15bx	61.37ax	83.97bx	62.08bx	92.65ax
Basal Cover	0.10	0.70	0.25	0.00	0.00	0.00
Pastures 1 & 2						
Native Grass Herbage	231.51ay	377.53ax	213.61by	474.07axz	354.31ayz	616.43bx
Basal Cover	2.55	8.65	6.80	7.60	7.65	6.45

Means in the same column and followed by the same letter (a, b, c) are not significantly different (P<0.05).
Means in the same row and followed by the same letter (x, y, z) are not significantly different (P<0.05).

Table 11. Mean annual domesticated and native grass herbage biomass (lbs/ac) and basal cover (%) on the silty ecological sites of three treatments on the Schnell Recreation Area, 2006-2011.

	Domesticated Grass		Native Grass	
Management Treatment	Herbage lbs/ac	Basal Cover %	Herbage lbs/ac	Basal Cover %
Nongrazed 4	1847.69a	12.97a	240.42a	1.46b
Pasture 3	1434.37b	13.83a	80.92b	0.18c
Pastures 1 & 2	847.25c	5.70b	377.91a	6.62a

Means in the same column and followed by the same letter (a, b, c) are not significantly different ($P<0.05$).

Table 12. Rhizosphere weight (kg) per cubic meter of soil at the Schnell Recreation Area, 2006-2011.

Nongrazed NR 4		May	Jul	Oct	Mean
2006	kg/m^3	52.23	74.41	66.09	64.24x
2007	kg/m^3	55.20	93.19	85.06	77.82x
2008	kg/m^3	69.35	70.62	72.05	70.67z
2009	kg/m^3	82.54	83.22	-	82.88z
2010	kg/m^3	87.74	96.54	76.27	86.85z
2011	kg/m^3	123.07	131.65	136.94	130.56z

Table 13. Rhizosphere weight (kg) per cubic meter of soil at the Schnell Recreation Area, 2006-2011.

Pasture NR 3		May	Jul	Oct	Mean
2006	kg/m^3	51.25	58.51	52.65	54.14x
2007	kg/m^3	37.53	84.52	92.96	71.67x
2008	kg/m^3	92.89	105.98	85.78	94.88y
2009	kg/m^3	128.35	97.74	-	113.05y
2010	kg/m^3	107.17	177.92	134.72	139.94y
2011	kg/m^3	164.54	167.55	169.06	167.05y

Table 14. Rhizosphere weight (kg) per cubic meter of soil at the Schnell Recreation Area, 2006-2011.

Pastures NR 1 & 2		May	Jul	Oct	Mean
2006	kg/m^3	91.36	86.10	72.38	83.28x
2007	kg/m^3	73.26	93.03	110.39	92.23x
2008	kg/m^3	109.24	129.72	128.86	122.61x
2009	kg/m^3	157.01	123.63	-	140.32x
2010	kg/m^3	200.02	193.86	155.13	183.00x
2011	kg/m^3	179.25	244.07	219.70	214.34x

Values in the “Mean” column of these three tables, in the same “year” row, and followed by the same letter are not significantly different ($P<0.05$).

Table 15. Grass relative composition (%) and rhizosphere weight (kg/m^3) for the nongrazed control 4 and grazed pasture NR 3 at the Schnell Recreation Area, 2006-2011.

	Grass Basal Cover Relative Composition (%)					
	Nongrazed Control NR 4			Grazed Pasture NR 3		
	Smooth Bromegrass	Kentucky Bluegrass	% Difference	Smooth Bromegrass	Kentucky Bluegrass	% Difference
2006	0.0	76.95	100.00	52.17	31.30	-40.00
2007	0.0	78.08	100.00	46.94	40.82	-13.04
2008	0.0	65.31	100.00	37.77	52.52	39.05
2009	0.0	80.53	100.00	44.44	49.32	10.98
2010	0.0	83.10	100.00	41.79	50.53	20.91
2011	0.28	85.96	100.00	28.82	64.71	124.53

	Rhizosphere Weight (kg/m^3)		
	Nongrazed Control NR 4	Grazed Pasture NR 3	% Difference
Pregrazing 2006	52.23	51.25	-1.88
2006	64.24x	54.14x	-15.72
2007	77.82x	71.67x	-7.90
2008	70.67z	94.88y	34.26
2009	82.88z	113.05y	36.40
2010	86.85z	139.94y	61.13
2011	130.56z	167.05y	27.95

Means in the same row and followed by the same letter (x, y, z) are not significantly different ($P<0.05$).

Table 16. Rhizosphere weight (kg/m^3) for the nongrazed control 4 and grazed pastures 1 & 2 during six years of twice-over rotation management, 2006-2011.

	Nongrazed Control 4 kg/m^3	Grazed Pastures 1 & 2 kg/m^3	% Difference
Pregrazing 2006	52.23	77.99	49.32
2006	64.24x	83.28x	29.64
2007	77.82x	92.22x	18.50
2008	70.67z	122.61x	73.50
2009	82.88z	140.32x	69.31
2010	86.85z	183.00x	110.71
2011	130.56z	214.34x	64.17

Means in the same row and followed by the same letter (x, y, z) are not significantly different ($P<0.05$).

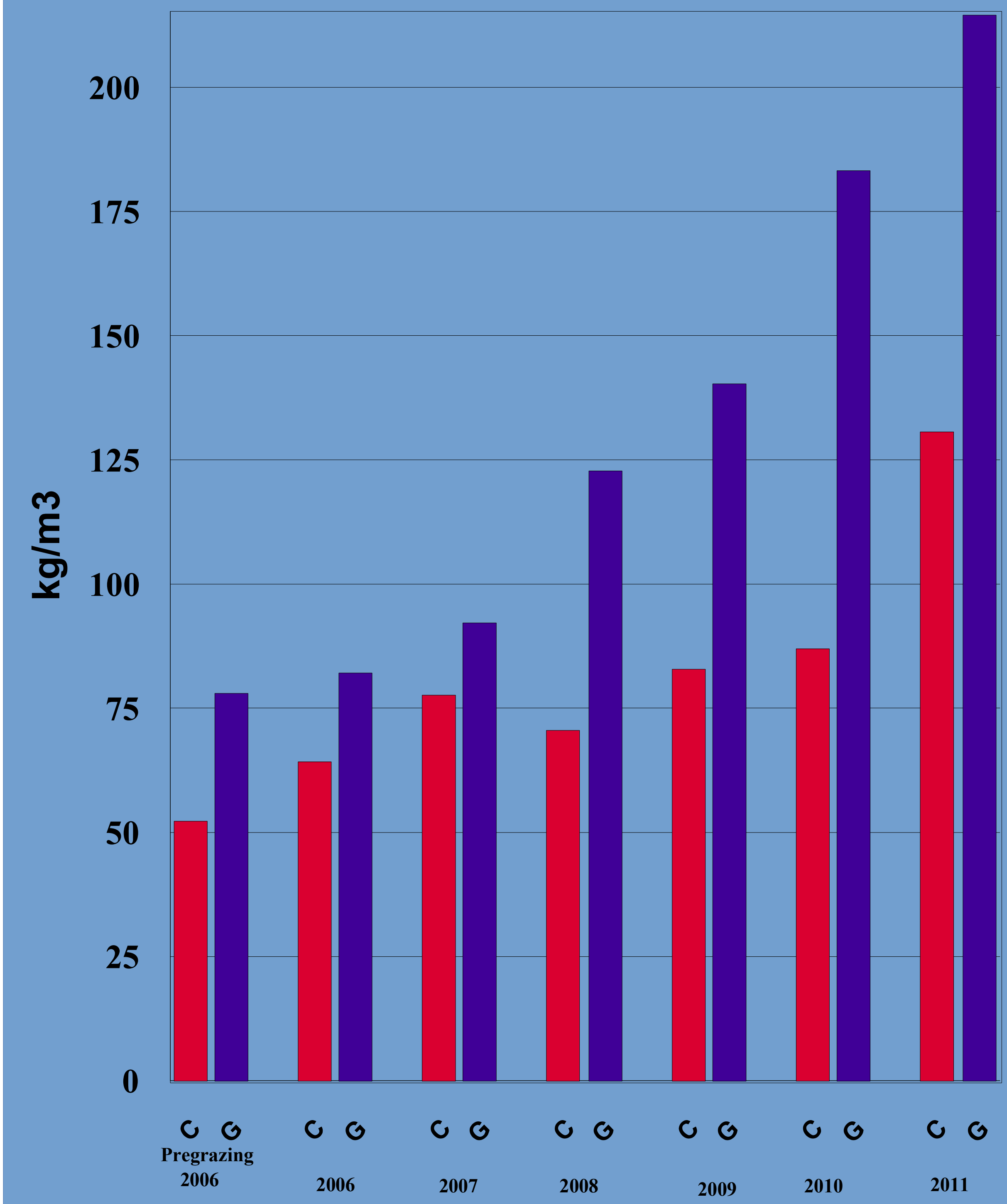

Figure 1. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Table 18. Mean annual domesticated and native grass herbage biomass (lbs/ac) and basal cover (%) on the silty ecological sites of three treatments on the Schnell Recreation Area, 2013-2014.

	Domesticated Grass		Native Grass	
Management Treatment	Herbage lbs/ac	Basal Cover %	Herbage lbs/ac	Basal Cover %
Nongrazed 4	2235.47a	19.03a	202.61ab	2.18b
Pasture 3	2232.26a	20.20a	56.50b	0.08c
Pastures 1 & 2	1057.41b	9.17b	419.13a	7.65a

Means in the same column and followed by the same letter (a, b, c) are not significantly different (P<0.05).

Table 19. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), at incremental depths in lbs/ac with quantities available in the soil and estimated quantities transformed to organic nitrogen during the growing season on silty ecological sites of the Schnell Recreation Area nongrazed 4, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	13.25	13.00	8.75	6.50	5.25	7.50
0-6 Transformed		-0.25	-4.50	-6.75	-8.00	-5.75
6-12 Available	9.75	6.75	6.00	5.00	4.25	4.25
6-12 Transformed		-3.00	-3.75	-4.75	-5.50	-5.50
12-24 Available	7.69	10.00	19.00	11.00	4.00	4.00
12-24 Transformed		+2.31	+11.31	+3.31	-3.69	-3.69
0-24 Available	30.69	29.75	33.75	22.50	13.50	15.75
0-24 Transformed		-0.94	+3.06	-8.19	-17.19	-14.94
NH_4 ammonium						
0-6 Available	19.99	11.83	16.24	12.40	13.79	13.63
0-6 Transformed		-8.16	-3.75	-7.59	-6.20	-6.36
6-12 Available	12.32	11.18	12.24	11.26	10.85	12.16
6-12 Transformed		-1.14	-0.08	-1.06	-1.47	-0.16
12-24 Available	8.24	13.14	16.16	12.07	12.40	3.65
12-24 Transformed		+4.90	+7.92	+3.83	+4.16	-4.59
0-24 Available	40.55	36.15	44.64	35.73	37.04	29.44
0-24 Transformed		-4.40	+4.09	-4.82	-3.51	-11.11
$NO_3 + NH_4$						
0-6 Available	33.24	24.83	24.99	18.90	19.04	21.13
0-6 Transformed		-8.41	-8.25	-14.34	-14.20	-12.11
6-12 Available	22.07	17.93	18.24	16.26	15.10	16.41
6-12 Transformed		-4.14	-3.83	-5.81	-6.97	-5.66
12-24 Available	15.93	23.14	35.16	23.07	16.40	7.65
12-24 Transformed		+7.21	+19.23	+7.14	+0.47	-8.28
0-24 Available	71.24	65.90	78.39	58.23	50.54	45.19
0-24 Transformed		-5.34	+7.15	-13.01	-20.70	-26.05

Table 20. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), at incremental depths in lbs/ac with quantities available in the soil and estimated quantities transformed to organic nitrogen during the growing season on silty ecological sites of the Schnell Recreation Area pasture 3, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	13.25	9.50	6.25	5.25	7.00	5.00
0-6 Transformed		-3.75	-7.00	-8.00	-6.25	-8.25
6-12 Available	6.00	8.00	4.75	3.75	5.25	4.00
6-12 Transformed		+2.00	-1.25	-2.25	-0.75	-2.00
12-24 Available	9.07	7.25	8.00	3.00	7.00	3.00
12-24 Transformed		-1.82	-1.07	-6.07	-2.07	-6.07
0-24 Available	28.32	24.75	19.00	12.00	19.25	12.00
0-24 Transformed		-3.57	-9.32	-16.32	-9.07	-16.32
NH_4 ammonium						
0-6 Available	14.12	15.91	11.02	11.10	14.36	12.97
0-6 Transformed		+1.79	-3.10	-3.02	+0.24	-1.15
6-12 Available	11.42	13.30	9.88	9.79	10.04	10.37
6-12 Transformed		+1.88	-1.54	-1.63	-1.38	-1.05
12-24 Available	10.60	12.57	10.28	10.45	12.40	3.30
12-24 Transformed		+1.97	-0.32	-0.15	+1.80	-7.30
0-24 Available	36.14	41.78	31.18	31.34	36.80	26.64
0-24 Transformed		+5.64	-4.96	-4.80	+0.66	-9.50
$NO_3 + NH_4$						
0-6 Available	27.37	25.41	17.27	16.35	21.36	17.97
0-6 Transformed		-1.96	-10.10	-11.02	-6.01	-9.40
6-12 Available	17.42	21.30	14.63	13.54	15.29	14.37
6-12 Transformed		+3.88	-2.79	-3.88	-2.13	-3.05
12-24 Available	19.66	19.82	18.28	13.45	19.40	6.30
12-24 Transformed		+0.16	-1.38	-6.21	-0.26	-13.36
0-24 Available	64.45	66.53	50.18	43.34	56.05	38.64
0-24 Transformed		+2.08	-14.27	-21.11	-8.40	-25.81

Table 21. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), at incremental depths in lbs/ac with quantities available in the soil and estimated quantities transformed to organic nitrogen during the growing season on silty ecological sites of the Schnell Recreation Area pastures 1 & 2, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	29.63	10.75	7.63	15.75	9.63	7.75
0-6 Transformed		-18.88	-22.00	-13.88	-20.00	-21.88
6-12 Available	11.38	4.88	4.88	4.38	4.25	4.63
6-12 Transformed		-6.50	-6.50	-7.00	-7.13	-6.75
12-24 Available	9.50	6.00	5.00	8.00	5.50	4.00
12-24 Transformed		-3.50	-4.50	-1.50	-4.00	-5.50
0-24 Available	50.50	21.63	17.51	28.13	19.38	16.38
0-24 Transformed		-28.87	-32.99	-22.37	-31.12	-34.12
NH_4 ammonium						
0-6 Available	20.21	14.44	14.77	16.88	19.00	14.81
0-6 Transformed		-5.77	-5.44	-3.33	-1.21	-5.40
6-12 Available	14.20	10.32	13.96	15.46	12.57	12.52
6-12 Transformed		-3.88	-0.24	+1.26	-1.63	-1.68
12-24 Available	14.45	11.67	14.44	11.99	13.30	3.88
12-24 Transformed		-2.78	-0.01	-2.46	-1.15	-10.57
0-24 Available	48.85	36.42	43.17	44.33	44.87	31.21
0-24 Transformed		-12.43	-5.68	-4.52	-3.98	-17.64
$NO_3 + NH_4$						
0-6 Available	49.83	25.19	22.39	32.63	28.62	22.56
0-6 Transformed		-24.64	-27.44	-17.20	-21.21	-27.27
6-12 Available	25.57	15.20	18.83	19.84	16.82	17.15
6-12 Transformed		-10.37	-6.74	-5.73	-8.75	-8.42
12-24 Available	23.95	17.67	19.44	19.99	18.80	7.88
12-24 Transformed		-6.28	-4.51	-3.96	-5.15	-16.07
0-24 Available	99.35	58.06	60.66	72.46	64.24	47.59
0-24 Transformed		-41.29	-38.69	-26.89	-35.11	-51.76

Table 22. Mean monthly (May-October) mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), at incremental depths in lbs/ac with quantities available in the soil and estimated quantities transformed to organic nitrogen during the growing season on silty ecological sites of the Schnell Recreation Area treatments, 2013-2014.

Soil Depth (inches)	Nongrazed 4	Pasture 3	Pastures 1 & 2
NO_3 nitrate			
0-6 Available	9.04	7.71	13.52
0-6 Transformed	-5.05	-6.65	-19.33
6-12 Available	6.00	5.29	5.73
6-12 Transformed	-4.50	-0.85	-6.78
12-24 Available	9.28	6.22	6.33
12-24 Transformed	+1.91	-3.42	-3.80
0-24 Available	24.32	19.22	25.59
0-24 Transformed	-7.64	-10.92	-29.89
NH_4 ammonium			
0-6 Available	14.65	13.25	16.69
0-6 Transformed	-6.41	-1.05	-4.23
6-12 Available	11.67	10.80	13.17
6-12 Transformed	-0.78	-0.74	-1.23
12-24 Available	10.94	9.93	11.62
12-24 Transformed	+3.24	-0.80	-3.39
0-24 Available	37.26	33.98	41.48
0-24 Transformed	-3.95	-2.59	-8.85
NO_3 + NH_4			
0-6 Available	23.69	20.96	30.20
0-6 Transformed	-11.46	-7.70	-23.55
6-12 Available	17.67	16.09	18.90
6-12 Transformed	-5.28	-1.59	-8.00
12-24 Available	20.23	16.15	17.96
12-24 Transformed	+5.15	-4.21	-7.19
0-24 Available	61.58	53.20	67.06
0-24 Transformed	-11.59	-13.50	-38.75

Table 23. May available and mean monthly transformed mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), at incremental depths in lbs/ac during the growing season on silty ecological sites of the Schnell Recreation Area treatments, 2013-2014.

Soil Depth (inches)	Nongrazed 4		Pasture 3		Pasture 1 & 2	
	May	Mean Monthly Transformed	May	Mean Monthly Transformed	May	Mean Monthly Transformed

	Available		Available		Available	
NO_3 nitrate						
0-6	13.25	5.05	13.25	6.65	29.63	19.33
6-12	9.75	4.50	6.00	0.85	11.38	6.78
12-24	7.69	+1.91	9.07	3.42	9.50	3.80
0-24	30.69	7.64	28.32	10.92	50.50	29.89
NH_4 ammonium						
0-6	19.99	6.41	14.12	1.05	20.21	4.23
6-12	12.32	0.78	11.42	0.74	14.20	1.23
12-24	8.24	+3.24	10.60	0.80	14.45	3.39
0-24	40.55	3.95	36.14	2.59	48.85	8.85
$NO_3 + NH_4$						
0-6	33.24	11.46	27.37	7.70	49.83	23.55
6-12	22.07	5.28	17.42	1.59	25.57	8.00
12-24	15.93	+5.15	19.66	4.21	23.95	7.19
0-24	71.24	11.59	64.45	13.50	99.35	38.75

Literature Cited

Barker, W.T., and W.C. Whitman. 1988. Vegetation of the Northern Great Plains. Rangelands 10:266-272.

Bloem, J., D.W. Hopkins, and A. Benedetti (eds.). 2006. Microbiological methods for assessing soil quality. CAB International, Oxfordshire, UK. 307p.

Brady, N.C. 1974. The nature and properties of soils. MacMillan Publishing Co., Inc., New York, NY. 639p.

Briske, D.D., and J.H. Richards. 1995. Plant response to defoliation: a physiological, morphological, and demographic evaluation. p. 635-710. *in* D.J. Bedunah and R.E. Sosebee (eds.). Wildland plants: physiological ecology and developmental morphology. Society for Range Management, Denver, CO.

Cook, C.W., and J. Stubbendieck. 1986. Range research: basic problems and techniques. Society for Range Management, Denver, CO. 317p.

Coyne, P.I., M.J. Trlica, and C.E. Owensby. 1995. Carbon and nitrogen dynamics in range plants. p. 59-167. *in* D.J. Bedunah and R.E. Sosebee (eds.). Wildland plants: physiological ecology and developmental morphology. Society for Range Management, Denver, CO.

Crider, F.J. 1955. Root-growth stoppage resulting from defoliation of grass. USDA Technical Bulletin 1102.

Goetz, H. 1975. Availability of nitrogen and other nutrients on four fertilized range sites during the active growing season. Journal of Range Management 28:305-310.

Grant, S.A., G.T. Barthram, L. Torvell, J. King, and H.K. Smith. 1983. Sward management, lamina turnover and tiller population density in continuously stocked *Lolium perenne*-dominated swards. Grass and Forage Science 38:333-344.

Kochy, M. 1999. Grass-tree interactions in western Canada. Ph.D. Dissertation. University of Regina. Regina, Saskatchewan, Canada.

Kochy, M., and S.D. Wilson. 2000. Competitive effects of shrubs and grasses in prairie. Oikos 91:385-395.

Langer, R.H.M. 1972. How grasses grow. Edward Arnold, London, Great Britain.

Legg, J.O. 1975. Influence of plants on nitrogen transformation in soils. pg. 221-227. *in* M.K. Wali (ed.). Prairie: A multiple view. University of North Dakota Press. Grand Forks, ND.

Manske, L.L. 1999. Can native prairie be sustained under livestock grazing? Provincial Museum of Alberta. Natural History Occasional Paper No. 24. Edmonton, Alberta. p.99-108.

Manske, L.L. 2007a. Effects on vegetation, endomycorrhizal fungi, and soil mineral nitrogen from prescribed burning treatments repeated every-other-year in mixed grass prairie invaded by western snowberry. NDSU Dickinson Research Extension Center. Summary Range Research Report DREC 07-3044. Dickinson, ND. 19p.

Manske, L.L. 2011b. Biology of defoliation by grazing. NDSU Dickinson Research Extension Center. Range Management Report DREC 11-1067b. Dickinson, ND. 25p.

Manske, L.L., and J.A. Urban. 2012. Humane soil beastie catcher: Its fabrication and use. NDSU Dickinson Research Extension Center. Range Research Report DREC 12-1079. Dickinson, ND. 9p.

Manske, L.L. 2014. Grazingland management based on native rangeland ecosystem mechanisms and processes. NDSU Dickinson Research Extension Center. Summary Range Management Report DREC 14-3062. Dickinson, ND. 18p.

Mosteller, F., and R.E.K. Rourke. 1973. Sturdy statistics. Addison-Wesley Publishing Co., MA. 395p.

Peltzer, D.A., and M. Kochy. 2001. Competitive effects of grasses and woody plants in mixed grass prairie. Journal of Ecology 89:519-527.

Power, J.F. 1970. Nitrogen management of semiarid grasslands in North America. Proceedings of the XI International Grassland Congress. 1970:468-471.

Shiflet, T.N. (ed.). 1994. Rangeland cover types. Society for Range Management. Denver, CO. 152p.

Whitman, W.C. 1975. Native range fertilization and interseeding study. Annual Report. Dickinson Experiment Station. Dickinson, ND. p. 11-16.

Wight, J.R., and A.L. Black. 1972. Energy fixation and precipitation use efficiency in a fertilized rangeland ecosystem of the Northern Great Plains. Journal of Range Management 25:376-380.

Wight, J.R., and A.L. Black. 1979. Range fertilization: plant response and water use. Journal of Range Management 32:345-349.