Evaluation of the Importance of Mineral Nitrogen Available at or Above Threshold Quantities in Maintaining Productivity at Potential Levels on Mixed Grass Prairie Ecosystems

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Before the 1862 Homestead Act of the United States and the 1872 Dominion Lands Act of Canada, agricultural producers of the world did not own the land where they lived and farmed. Part of the commodities produced were used as rent and part of the crops and animals they raised belonged to the producer. These produced commodities were more important for family survival than the land. The land management practices that were developed were based on the use. All of the renewable natural resources (rangelands, grasslands, croplands, forestlands, and fisheries) are still traditionally managed for their use. As a result, the productivity of the worlds natural resources are gradually deteriorating. Traditional management for the "use" does not take the renewable natural resources back to the "good as new" condition.

Traditional management practices neglect the vital cryptobiotic microorganism component. The microorganisms are the renewable portion of natural resource ecosystems. Microbes cycle essential elements from the unusable organic forms into the usable mineral forms. Reductions in microorganism quantity or activity translates into reduction in usable essential elements. Diminishment in the quantity of available essential elements is the deterioration in productivity of natural resources (Bloem et al. 2006).

The major essential elements in native grassland ecosystems are carbon, hydrogen, nitrogen, and oxygen. The minor essential elements are the macronutrients and the micronutrients, and the presence of sunlight energy is essential.

Radiant light from the sun is the ecosystem input source for energy. Radiant energy from the sun is necessary for photosynthesis. Sunlight is not limiting on rangelands even with about 30% cloud cover, except the intensity of sunlight can be greatly reduced by shading from taller grasses and shrubs (Kochy 1999). The light levels penetrating the leaf canopy can be about 20% of the light levels above the canopy (Peltzer and Kochy 2001).

Atmospheric carbon dioxide (CO_2) is the ecosystem input source for carbon. Atmospheric carbon dioxide which composes about 0.03% of the gasses in the atmosphere is not limiting on rangelands. The carbon dioxide is fixed with hydrogen from soil water during photosynthesis which converts energy from sunlight into chemical energy and assimilates simple carbohydrates. Capturing energy by fixing carbon has a relatively low impact on the plant organisms that possess chlorophyll and has low biological costs to the ecosystem resources (Manske 2011a).

Soil water (H_2O) is infiltrated precipitation water and is the ecosystem input source for hydrogen. Soil water is absorbed through the roots and distributed throughout the plant within the xylem vascular tissue. Water deficiency conditions in western North Dakota have a long-term periodicity rate at 32.7%, for a mean of 2.0 months with water deficiency during the 6.0 month perennial plant growing season (Manske et al. 2010). Water is necessary for plant growth. However, deficiencies in mineral nitrogen limit herbage production more often than water deficiencies in temperate grasslands (Tilman 1990).

Carbon dioxide, water, and nitrogen oxides are the ecosystem input sources for oxygen. Atmospheric oxygen composes about 28% of the gasses in the atmosphere. The oxygen cycle is closely linked to the carbon cycle and the water, or hydrological cycle. Oxygen is vital for all organisms that carry out aerobic respiration. Oxygen is not limiting on rangeland ecosystems.

Wet deposition of nitrogen oxides (NO, N_2O) following lightning discharges is the ecosystem input source for nitrogen (Manske 2009a). The source of nitrogen for plant growth is mineral nitrogen (NO_3 nitrate, NH_4 ammonium) converted from soil organic nitrogen by rhizosphere microorganisms. 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). The quantity of rhizosphere microorganism biomass is the limiting factor in rangeland ecosystems with low mineral nitrogen available. Biomass and activity of microorganisms in the rhizosphere are limited by access to short chain carbon energy which can be exudated from grass lead tillers with partial defoliation by grazing graminivores when grass tillers are at vegetative growth stages between the three and a half new leaf stage and the flower stage. Transforming nitrogen from organic nitrogen into mineral nitrogen and back to organic nitrogen is complex and has a great impact on many organisms at multiple trophic levels and has high biological costs on the ecosystem resources (Manske 2011a, 2014a).

Failure of traditional management practices to replenish ecosystem available essential elements at quantities equal to or greater than the annual amount of essential elements needed for ecosystem functioning at biological potential levels that have resulted from incremental decreases in microorganism biomass is the primary factor causing deterioration in productivity of natural resources.

The objectives of this study are to show the importance of purposeful management of the quantity of available mineral nitrogen to be at 100 lbs/ac or greater on native grassland ecosystems in order to renew the ecosystem condition back to “good as new” and to maintain vegetation and livestock production at potential levels.

Study Area

The native rangeland study sites were on the Dickinson Research Extension Center (DREC) ranch, operated by North Dakota State University (NDSU), and located in Dunn County, 20 miles north of Dickinson, in western North Dakota, USA.

Long-term mean annual temperature was 42.1° F (5.7° C). January was the coldest month, with a mean temperature of 14.6° F (-9.7° C). July and August were the warmest months, with mean temperatures of 69.6° F (20.9° C) and 68.5° F (20.3° C), respectively. Long-term mean annual precipitation was 17.2 inches (437.7 mm). The amount of precipitation received during the perennial plant growing season (April to October) was 14.5 inches (368.8 mm) and was 84.3% of annual precipitation (Manske 2015a).

Soils were primarily Typic Haploborolls. 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

Three management treatments were evaluated (1) long-term nongrazed control (NG), (2) 4.5-month seasonlong (4.5-m SL), and (3) 4.5-month twice-over rotation system (4.5-m TOR).

The long-term nongrazed control management treatment was designed with two large replicated exclosures and had not been grazed, mowed, or burned for more than 30 years before the initiation of the research treatments in 1983.

The 4.5-month seasonlong grazing system was designed with two replicated pastures. Each pasture was grazed for 137 days from early June to mid October stocked at 2.86 acres per cow-calf pair per month.

The 4.5-month twice-over rotation grazing system was designed with two replicated systems each with three pastures. Each pasture was grazed two times per growing season. Each system was grazed 137 days from early June to mid October stocked at 2.20 acres per cow-calf pair per month.

Procedure

Temperature and precipitation data was taken from historical climatological data collected at the Dickinson Research Extension Center (DREC) ranch, latitude 47° 14' N, longitude 102° 50' W, Dunn County, near Manning, North Dakota, USA, 2013-2014.

Available soil water (reported as inches of water) was determined by the gravimetric procedure from two replications of soil core samples collected at silty ecological sites of each management treatment with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, 12-24, 24-36, and 36-48 inches on monthly periods during April to October, 2013-2014.

Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986). The herbage biomass was partially defoliated by the selected grazing management on the seasonlong and twice-over treatments. The nongrazed exclosure areas 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 monthly (May to October) from five 0.25 m^2 quadrats (frames) at two replicated silty ecological sample sites for each of the study treatments during 2013 and 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. The native grass (cool and warm season grass) and domesticated grass herbage biomass weights were reported for this study. The domesticated grass weights were too small to measure (<10 g/¼ m^2).

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

Rhizosphere volume associated with western wheatgrass (Agropyron smithii) roots was determined from two replicated intact soil cores from silty ecological sites on each of the study treatments collected monthly (June to September) during 2002. Plastic PVC pipe 3 inches (7.62 cm) in diameter and 4 inches (10.16 cm) long was forced into sample site soil. Intact soil-plant cores and pipe were excavated and transported to the laboratory. The soil matrix of collected soil cores was carefully removed from between the rhizospheres around the roots of western wheatgrass plants. The exposed rhizospheres were sprayed with a clear acrylic coating to prevent damage during further handling. The length and diameter of the rhizosphere around each root of every plant, including associated tillers, were measured in inches with a vernier caliper, then converted to metric system values. The length and diameter measurements were used to determine the volume of each rhizosphere. Data were analyzed on a per-plant basis, as a total of all plants per replication, and reported as a mean of the two replications per sample period.

Soil weight of silty soil in southwestern North Dakota was determined from average silty soil bulk density from analysis of comparable soils (Anonymous circa early 1980's) at incremental depths of 0-6, 6-12, 12-24, 24-36, and 36-48 inches. Weight of soil organic matter (SOM) was determined from the soil weight of silty soil and percent soil organic matter from analysis conducted by the North Dakota State University Soil Testing Laboratory of soil core samples from four replicated cores on silty ecological sites of each management treatment at incremental depths of 0-6, 6-12, 12-24, 24-36, and 36-48 inches collected during June of 2013 and 2014. Weight of soil organic carbon (SOC) was determined from the soil weight of silty soil and percent soil organic matter multiplied by 0.58 (58% organic carbon content of soil organic matter) (Anonymous nd, NRCS Staff 2009, Pluske et al. 2015) of soil core samples on silty ecological sites of each management treatment at incremental depths of 0-6, 6-12, 12-24, 24-36, and 36-48 inches. Weight of soil organic nitrogen (SON) was determined from the soil weight of silty soil and percent soil organic matter multiplied by 0.058 (estimated 5.8% organic nitrogen content of soil organic matter) of soil core samples on silty ecological sites of each management treatment at incremental depths of 0-6, 6-12, 12-24, 24-36, and 36-48 inches (table 1).

Soil mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), was determined from four replicated soil core samples collected at silty ecological sites inside protective exclosures for the nongrazed treatment, and outside exclosures exposed to selected treatments for the seasonlong and twice-over rotation grazing management systems with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, 12-24 inches on monthly periods during May to October of 2013 and 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 (table 1)

(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 2013 and 2014 growing seasons at the Dickinson Research Extension Center (DREC) ranch was generally favorable with the mean two year growing season precipitation at 20.46 inches (140.87% of LTM). None of the growing season months of 2013 experienced water deficiency conditions and during 2014, July, September, and October had water deficiency conditions, however, the total growing season of 2014 received 19.35 inches of precipitation (133.26% of LTM). Mean precipitation of 2013 and 2014 growing season months indicated that means of July had water deficiency conditions and means of May, August, and October had wet conditions with mean monthly precipitation at 4.48 inches (216.58% of LTM) (table 2) (Manske 2015a).

Available soil water at increments down to 48 inches during the growing season months, April to October, in 2013 and 2014 was high on the nongrazed, seasonlong, and twice-over management treatments. The twice-over treatment had significantly greater soil water than that on the nongrazed treatment. The quantity of soil water on the seasonlong treatment was not significantly different than that on the nongrazed and twice-over treatments. A strong trend with greater soil water can be seen during June to October on the twice-over treatment and the available soil water on the seasonlong treatment showed a trend of lower quantities each growing season month, May to September. During the grazing season, June to October, the soil column, 0 to 48 inches, on twice-over treatment had the greatest quantity of soil water; 23.1% greater than that on the seasonlong and 54.0% greater than that on the nongrazed treatments. The seasonlong treatment had 25.1% greater soil water than that on the nongrazed treatment. The twice-over treatment had the greatest quantity of soil water in the top 12 inches; 19.6% greater than that on the seasonlong and 51.5% greater than that on the nongrazed (table 3). The rhizosphere microorganisms on the nongrazed, seasonlong, and twice-over treatments should have had adequate soil water to flourish at all of the incremental depths down to 48 inches, during each growing season month, April to October, and during both years, 2013-2014 (table 3).

Precipitation during August of 2013 and 2014 was wet with a monthly mean of 5.83 inches (298.72% of LTM) (table 2). During August, soil water at the 0 to 12 inch soil depth on the twice-over treatment was 25.6% greater than that on the seasonlong and 67.8% greater than that on the nongrazed treatments. Soil water at the 12-48 inch soil depth on the twice-over treatment was 50.7% greater than that on the nongrazed treatment. The twice-over treatment had 43.9% greater soil water than that on the seasonlong treatment at the 12 to 48 inch soil depth during August. These data indicate that a high percentage of the high August rainfall infiltrated into the soil on the twice-over treatment. The infiltrated soil water on the twice-over treatment moved downward slowly remaining in the 0-48 inch soil column. A much smaller percentage of the high August rainfall infiltrated into the soil on the nongrazed and seasonlong treatments and did not move downward into the 12 to 48 inch soil depths (table 3).

The quantity of soil water during the growing season was greatest on the twice-over treatment because of the greater amount of aggregation of the soil particles that result from the greater biomass of both endomycorrhizal fungi and ectomycorrhizal fungi (Manske 2011a). Endomycorrhizal fungi secrete great quantities of adhesive polysaccharides that bond soil particles around active grass roots forming the structural environment for symbiotic rhizosphere microorganisms, and this adhesive polysaccharid also binds soil particles into aggregates resulting in increased soil pore spaces, increased water holding capacity, and increased rooting depth. Ectomycorrhizal fungi secrete large amounts of adhesive polysaccharids forming water-stable aggregates in soil that are water permeable but not water soluable causing increased soil aggregation at increased soil profile depths resulting in improved soil structure and quality, increased soil oxygenation, increased water infiltration and water holding capacity, and decreased erodibility (Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat 2003, Manske 2007).

The aboveground native grass herbage biomass was greatest on the nongrazed treatment. During the grazing season, herbage biomass on the nongrazed treatment was 66.0% greater than the grazed herbage biomass remaining on the seasonlong and 16.7% greater than the grazed herbage biomass remaining on twice-over treatments (tables 4 and 5). The herbage biomass remaining after grazing was 42.3% greater on the twice-over treatment than that on the seasonlong treatment. The stocking rate on the twice-over treatment was 28.6% greater than that on the seasonlong treatment and the quantity of herbage removed by grazing cows would have been 28.6% greater per acre on the twice-over treatment than that on the seasonlong treatment.

During 2013 and 2014, the production of native grass herbage biomass was greater on the twice-over treatment than that on the seasonlong treatment. Native grass lead tiller herbage growth on the twice-over treatment was 23.9% greater, the quantity removed by grazing was 28.6% greater, the herbage residuum after grazing was 22.5% greater, the regrowth of secondary tiller herbage was 160.0% greater, and the herbage residuum and regrowth after grazing was 42.3% greater than those on the seasonlong treatment. The quantity of herbage removed by grazing and the quantity of herbage regrowth after grazing was 70.9% greater on the twice-over treatment than that on the seasonlong treatment.

Some domesticated grass herbage biomass grew on all three treatments, however, collection of that quantity by the standard herbage clipping method was too small to measure (table 5). The basal cover of domesticated grasses was also very low with only a small quantity of plants located by the ten-pin point frame method (table 5).

Basal cover of native grasses was significantly greater on the twice-over treatment than that on the seasonlong and nongrazed treatments (table 5). Native grass basal cover on the twice-over treatment was 193.6% greater than that on the nongrazed and 27.3% greater than that on the seasonlong treatments. Basal cover of native grasses was significantly greater on the seasonlong treatment than that on the nongrazed treatment (table 5). Native grass basal cover on the seasonlong treatment was 130.6% greater than that on the nongrazed treatment.

The quantity of native grass herbage biomass was greater on the twice-over treatment because of the greater rhizosphere microorganism biomass and the greater activation of the defoliation resistance mechanisms that increased the quantity of major and minor essential elements being cycled by the biogeochemical processes from organic forms into available mineral forms. Greater quantities of available mineral nitrogen and fixed carbon promoted greater growth and development of plant material through the compensatory physiological processes. Greater grass herbage biomass was produced that permitted a greater stocking rate with greater quantities of herbage removed by grazing livestock that was replaced by greater quantities of regrowth leaving greater quantities of vegetation after each of the two grazing periods (Manske 2011a, 2014a).

The quantity of native grass basal cover was greater on the twice-over treatment because the greater quantities of available mineral nitrogen and fixed carbon promoted greater numbers of secondary tillers from axillary buds to grow and develop through the processes of vegetative reproduction (Manske 2011a, 2014a).

The rhizosphere microorganism biomass cannot easily be measured directly. With painstaking care, volume of the rhizosphere cylinders around active perennial grass roots can be quantitatively measured. During the growing season of 2002, accurate replicated rhizosphere volume measurements were collected (Gorder, Manske, Stroh 2004). The rhizosphere volume per cubic meter of soil was not different during June on the nongrazed, seasonlong, and twice-over treatments, and the rhizosphere volume on the nongrazed and twice-over treatments were not different during July. The rhizosphere volume on the nongrazed and seasonlong treatments were not different during August and September (table 6 and figure 1). The first grazing period on the twice-over treatment pasture 3 was 15 days during early July to mid July. This grazing period stimulated the rhizosphere microorganisms to increase in quantity and biomass causing the volume to increase from 3900 cm^3/m^3 during July to 7200 cm^3/m^3 during August for an 85.6% increase in volume. The rhizosphere volume on the twice-over treatment pasture 3 decreased slightly during low precipitation occurring in September. The rhizosphere volume during August and September on the twice-over treatment was significantly greater than those on the nongrazed and seasonlong treatments (table 6 and figure 1). The rhizosphere volume on the twice-over treatment was 265.9% greater than that on the seasonlong and was 200.3% greater than that on the nongrazed treatments during August.

The western wheatgrass tiller density associated with the rhizosphere sample cores during the grazing season of 2002 was 1754.25 tillers/m^2 on the twice-over treatment and was significantly greater than the tiller density of 657.84 tillers/m^2 on the seasonlong and was significantly greater than the tiller density of 794.89 tillers/m^2 on the nongrazed treatments. The tiller density on the twice-over treatment was 166.7% greater than that on the seasonlong and was 120.7% greater than that on the nongrazed trreatments (Gorder, Manske, Stroh 2004).

The great increase in rhizosphere volume on the twice-over treatment after July was caused by partial defoliation by grazing cows during 15 days from early July to mid July that removed 25% to 33% of the leaf biomass of lead tillers at vegetative phenological growth stages between the three and a half new leaf stage and the flower stage which activated exudation of short chain carbon energy from the grass tillers through the roots and released into the rhizosphere where microorganisms could rapidly increase in number and biomass by ingesting the needed energy that had been limiting growth and development.

The greater rhizosphere volume on the twice-over treatment had a greater rhizosphere microorganism biomass that mineralized a greater quantity of organic nitrogen into mineral nitrogen. The greater quantity of available mineral nitrogen was the essential nutrient needed to support a greater grass tiller density, a greater production of grass herbage biomass, and a greater production grass regrowth following grazing (Manske 2011a, 2014a).

Percent soil organic matter (SOM) was determined at the NDSU soil testing laboratory from soil cores collected on silty ecological sites. Determination of the weight of the soil organic matter required the determination of the weight of silty soil at each incremental depth from average soil bulk density data (Anonymous circa early 1980's) of all incremental depths (table 7).

Percent (%) and weight (lbs/ac, tons/ac) of soil organic matter was greatest on the twice-over treatment. Soil organic matter (SOM) on the twice-over (3.20%, 231.5 tons/ac) treatment had 11.7% greater percent and 13.5% greater weight than that on the seasonlong (2.82%, 203.9 tons/ac) and had 54.1% greater percent and 116.9% greater weight than that on the nongrazed (1.47%, 106.7 tons/ac) treatments. Soil organic matter on the seasonlong treatment had 47.9% greater percent and 91.1% greater weight than that on the nongrazed treatment (table 8).

Soil organic carbon (SOC) composes 58% of the soil organic matter (Anonymous nd, NRCS Staff 2009, Pluske et al. 2015). The weight of soil organic carbon is 58% of the weight of soil organic matter. The weight of soil organic carbon (SOC) was greater on the twice-over (1.85%, 134.1 tons/ac) treatment than that on the seasonlong (1.63%, 118.2 tons/ac) and nongrazed (0.86%, 62.0 tons/ac) treatments. The weight of soil organic carbon was greater on the seasonlong treatment than that on the nongrazed treatment (table 9).

Soil organic nitrogen (SON) has been estimated to compose 5.8% of the soil organic matter. The weight of soil organic nitrogen (SON) was greater on the twice-over (0.185%, 13.4 tons/ac) treatment than that on the seasonlong (0.163%, 11.8 tons/ac) and nongrazed (0.086%, 6.2 tons/ac) treatments. The weight of soil organic nitrogen was greater on the seasonlong treatment than that on the nongrazed treatment (table 10).

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 increase in June, transformation would increase with available mineral nitrogen at a low value during late June to 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 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 the nongrazed treatment had a peak during May at the 0-6, and 6-12, inch soil depths (table 11). Generally, available mineral nitrate and transformation were low during the growing season at all soil depths. There was a decrease in available mineral nitrate and an increase in transformation during July and again during October at all soil depths. There was an increase in available mineral nitrate and a decrease in transformation during September at the 0-6 inch soil depth (table 11).

Ammonium (NH_4) cycle on the nongrazed treatment had a peak during May at the 0-6 inch soil depth (table 11). Generally, available mineral ammonium was moderate during the growing season at all soil depths and transformation was moderate at the 0-6 inch soil depth and was extremely low or accumulating at the 6-12 and 12-24 inch soil depths. There was a decrease in available mineral ammonium and an increase in transformation during August at the 0-6 inch soil depth. There was an increase in available mineral ammonium and a decrease in transformation during October at the 0-6 inch soil depth (table 11).

Nitrate (NO_3) cycle on the seasonlong treatment had a peak during May at the 0-6 inch soil depth and had minor peaks at the 6-12 and 12-24 inch soil depths (table 12). Generally, available mineral nitrate was relatively high and transformation was moderate during the growing season at all soil depths. There was a decrease in available mineral nitrate and an increase in transformation during July and again during October at the 0-24 inch soil depth. There was an increase in available mineral nitrate and a decrease in transformation during August and September at the 0-6 and 12-24 inch soil depths (table 12).

Ammonium (NH_4) cycle on the seasonlong treatment had a peak during May at the 0-6 inch soil depth. Generally, available mineral ammonium was low during the growing season at all soil depths and transformation was low at the 0-6 inch soil depth, very low or accumulating at the 6-12 inch soil depth, and very low at the 12-24 inch soil depth. Available mineral ammonium and transformation changed little during July, August, and September at all soil depths (table 12).

Nitrate (NO_3) cycle on the twice-over treatment had a peak during May at the 0-6, 6-12, and 12-24 inch soil depths (table 13). Generally, available mineral nitrate was low and transformation was high during July, August, September, and October at all soil depths. There was a decrease in available mineral nitrate and an increase in transformation during July and again during October at all soil depths. There was an increase in available mineral nitrate and a decrease in transformation during September at the 0-6 and 6-12 inch soil depths (table 13).

Ammonium (NH_4) cycle on the twice-over treatment had a peak during May at the 0-6 inch soil depth. Generally, available mineral ammonium was high and transformation was high during the growing season at all soil depths. There was an increase in available mineral ammonium and a decrease in transformation during August and again during October at all soil depths. There was a decrease in available mineral ammonium and an increase in transformation during July and again during September at the 0-6 and 12-24 inch soil depths (table 13).

The reference high peak available mineral nitrogen ($NO_3 + NH_4$) occurs during mid May. The greatest available mineral nitrogen was on the twice-over treatment and the lowest was on the nongrazed treatment. Available mineral nitrogen on the twice-over treatment was 19.4% greater than that on the seasonlong and was 75.6% greater than that on the nongrazed treatments. Available mineral nitrogen on the seasonlong treatment was 47.1% greater than that on the nongrazed treatment (table 14). The twice-over treatment was the only treatment with mineral nitrogen available at quantities greater than 100 lbs/ac. During May, both nitrate (NO_3) and ammonium (NH_4) were available at greater quantities at each soil depth on the twice-over treatment than those on the seasonlong and nongrazed treatments.

During May (table 14), available mineral nitrate (NO_3) was greatest on the twice-over treatment. Available mineral nitrate on the twice-over treatment was 16.9% greater than that on the seasonlong and was 166.9% greater than that on the nongrazed treatments. Available mineral nitrate on the seasonlong treatment was 128.4% greater than that on the nongrazed treatment.

During May (table 14), available mineral ammonium (NH_4) was greatest on the twice-over treatment. Available mineral ammonium on the twice-over treatment was 21.3% greater than that on the seasonlong and was 40.5% greater than that on the nongrazed treatments. Available mineral ammonium on the seasonlong treatment was 15.8% greater than that on the nongrazed treatment.

During the growing season, available mineral nitrogen ($NO_3 + NH_4$) was greatest on the twice-over treatment. Available mineral nitrogen on the twice-over treatment was 9.8% greater than that on the seasonlong and was 41.7% greater than that on the nongrazed treatments. Available mineral nitrogen on the seasonlong treatment was 29.0% greater than that on the nongrazed treatment (table 15).

During the growing season (table 15), available mineral nitrate (NO_3) on the twice-over treatment was 85.6% greater than that on the nongrazed treatment. Available mineral nitrate on the seasonlong treatment was 1.9% greater than that on the twice-over treatment and was 89.2% greater than that on the nongrazed treatment.

During the growing season (table 15), available mineral ammonium (NH_4) on the twice-over treatment was 14.9% greater than that on the seasonlong and was 30.2% greater than that on the nongrazed treatments. Available mineral ammonium on the seasonlong treatment was 13.3% greater than that on the nongrazed treatment. Mineral ammonium tended to accumulate at the 6 to 24 inch soil depths on the nongrazed treatment (table 15).

Transformation of mineral nitrogen was greatest on twice-over treatment. Transformation of mineral nitrogen on the twice-over treatment was 48.0% greater than that on the seasonlong and was 276.8% greater than that on the nongrazed treatments. Transformation of mineral nitrogen on the seasonlong treatment was 154.5% greater than that on the nongrazed treatment (table 15). Mineral nitrogen from the lower soil depths was tranformed in greater quantities on the twice-over treatment. Transformed mineral nitrogen on the twice-over treatment from the 6 to 24 inch soil depths was 76.0% greater than that used on the seasonlong and was 194.2% greater than that used on the nongrazed treatments (table 15).

Transformation of mineral nitrate (NO_3) on the twice-over treatment was 37.7% greater than that on the seasonlong and was 307.0% greater than that on the nongrazed treatments. Transformation of mineral nitrate on the seasonlong treatment was 195.7% greater than that on the nongrazed treatment (table 15).

Transformation of mineral ammonium (NH_4) on the twice-over treatment was 95.5% greater than that on the seasonlong and was 203.0% greater than that on the nongrazed treatments. Transformation of mineral ammonium on the seasonlong treatment was 55.0% greater than that on the nongrazed treatment (table 15).

The quantity of available mineral nitrogen was greater than 100 lbs/ac on the twice-over treatment and the quantity of available mineral nitrate and mineral ammonium during May and during the growing season was greatest on the twice-over treatment because the rhizosphere microorganism biomass was greater. The rhizosphere microorganism biomass was greater on the twice-over treatment as a result of two grazing periods that coordinated grazing activity with grass phenological growth that resulted in greater quantities of short chain carbon energy to be exudated into the rhizosphere for the microorganisms from the roots of partially defoliated vegetative lead tillers during the first grazing period between early June and mid July. The increased energy increased the microbe biomass; the greater microbe biomass mineralized greater quantities of organic nitrogen into mineral nitrogen. Microbial digestion produces ammonia and ammonium. The ammonia can readily be hydrolyzed into stable ammonium. Some of the ammonium can be oxidized during nitrification to produce nitrate. These processes result in greater quantities of available mineral nitrate and mineral ammonium (Manske 1999, 2009a, 2009b, 2011a, 2014a, 2015b).

The quantity of mineral nitrate and mineral ammonium transformed (immobilized) was greatest on the twice-over treatment because the high activity of the defoliation resistance mechanisms was producing greater quantities of herbage biomass, vegetative tillers, and regrowth leaves and shoots and the greater quantity of soil microorganisms were maintaining and increasing their biomass requiring the use of greater quantities of mineral nitrogen (Manske 2011a, 2014a).

The cow and calf weight performance on the twice-over treatment has been greater for 21 years than that on the seasonlong treatment (table 16). Calves on the twice-over treatment have accumulated 13.9% greater weight, gained 14.1% greater weight per day, and gained 33.8% greater weight per acre than the calves on the seasonlong treatment. Cows on the twice-over treatment have accumulated 81.7% greater weight, gained 131.0% greater weight per day, and gained 183.7% greater weight per acre than the cows on the seasonlong treatment.

The quantity of cow and calf weight performance was greatest on the twice-over treatment because of the increased production and quality of the herbage biomass, vegetative tillers, and regrowth biomass. The increased herbage biomass permitted the greater stocking rate without harming the vegetation. The greater vegetative tillers and regrowth biomass provide greater forage of higher quality that permitted the cows to produce milk closer to their genetic potential that permitted the calves to grow closer to their genetic potential during the period from mid July to mid October when traditional practices provide forage with quality below the livestock requirements (Manske 2008a, 2008b, 2008c, 2014b).

Discussion

The "good as new" condition for native grassland ecosystems in the Northern Plains produces herbage biomass, vegetative tillers, and regrowth of stems and leaves at potential levels and cow and calf weight performance at near genetic potentials. These potential levels of production are reached when soil mineral nitrogen is available at threshold quantities of 100 lbs/ac or greater.

The weight of soil organic nitrogen was 13.4 tons/ac on the twice-over treatment, 11.8 tons/ac on the seasonlong treatment, and 6.2 tons/ac on the nongrazed treatment. Soil organic nitrogen in the silty ecological sites was adequately abundant on all three treatments. Plants cannot use organic nitrogen. The reference high peak level of mineral nitrogen during mid May (at time 1) was available at 102.6 lbs/ac on the twice-over treatment, 85.9 lbs/ac on the seasonlong treatment, and 58.4 lbs/ac on the nongrazed treatment. The twice-over treatment was the only management strategy with mineral nitrogen available at or above the threshold quantity of 100 lbs/ac. Both the nongrazed and seasonlong treatments had deficiencies in the quantity of available mineral nitrogen.

Conversion of soil organic nitrogen into 100 lbs/ac of available mineral nitrogen is a complex process, requires a great biomass of rhizosphere microorganisms, and has high biological costs for the ecosystem. The primary producer trophic level in the rhizosphere are achlorophyllous saprophytes and cannot fix carbon for energy. The rhizosphere microorganism biomass and activity are limited by access to short chain carbon energy (Manske 2011a, 2014a). Greater quantities of short chain carbon compounds are produced during photosynthesis than healthy grass tillers need for growth and development (Coyne et al. 1995). Some of this surplus short chain carbon energy can be moved from the grass tiller through the roots into the rhizosphere with partial defoliation by large grazing graminivores.

The twice-over rotation strategy has two grazing periods on each pasture of a three to six pasture system. The periods of partial defoliation by grazing are coordinated with the grass tillers phenological growth stages. Grazing on each of the pastures during the first period (1 June to 15 July) removes 25% to 33% of the leaf weight of grass lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage that fully activates the defoliation resistance mechanisms (Manske 1999, 2011a, 2014a).

Full activation of the compensatory physiological processes within grass plants accelerates growth rates of replacement leaves and shoots, increases photosynthetic capacity of remaining mature leaves that increases the quantity of available fixed carbon, 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 processes of vegetative production increases secondary tiller development from axillary buds, increases initiated tiller density during the grazing season, and increases herbage biomass production and improves herbage nutritional quality.

Full activation of the external symbiotic rhizosphere organism activity occurs with the exudation of adequate quantities of surplus short chain carbon energy that increases microorganism numbers and biomass that increases rhizosphere volume, increases ecosystem biogeochemical cycling of essential elements, increases soil aggregation that improves water infiltration and increases soil water holding capacity, increases soil organic matter, soil organic carbon, and soil organic nitrogen, increases mineralization of soil organic nitrogen that increases the quantity of available mineral nitrogen, and improves belowground resource uptake competitiveness.

During the second grazing period (mid July to mid October) each pasture is grazed for double the number of days it was grazed the during first period. Because the greater herbage biomass resulting from the increased growth of replacement herbage and the increased tiller density (basal cover) and greater nutritional quality from the great number of secondary vegetative tillers that have developed past the three and a half new leaf stage, the cow and calf weight performance is improved. The stocking rates are increased without harming the vegetation. The lactating cows gain weight and produce milk close to their genetic potential and their calves gain weight at or near their genetic potential during the entire grazing season.

Grass plants, soil organisms, and graminivores have developed numerous complex symbiotic mechanisms and processes. The twice-over rotation grazing strategy is designed to fully activate and maintain these defoliation resistance mechanisms so that the ecosystem biogeochemical processes function at potential levels, that the biological requirements for all of the biotic organisms are met, and that the native grassland ecosystems are fully renewed back to the “good as new” condition.

Acknowledgment

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Table 1. Weight of soil, soil organic matter (SOM), soil organic carbon (SOC), and soil organic nitrogen (SON) in pounds per acre per incremental depth and the quantity of transformed nitrogen.

Mathematical Formula
Soil weight per increment of soil depth per acre
Soil bulk density in g/cm^3 X depth of soil in cm X 100,000,000 cm^2/1 hectare
X 1 ha/2.471 ac X 1 lb/453.5924 g = soil weight in lbs/ac
Weight of soil organic matter (SOM)
Weight of soil in lbs/ac X % SOM/100 = weight of SOM in lbs/ac
Weight of soil organic carbon (SOC)
Weight of soil in lbs/ac X (% SOM/100 X 0.58) = weight of SOC in lbs/ac
Weight of soil organic nitrogen (SON)
Weight of soil in lbs/ac X (% SOM/100 X 0.058) = weight of SON in lbs/ac
Net mineralization measurements of the nitrogen balance equation
$M = \Delta NH_4 + \Delta NO_3 + \Delta \text{Plant} + \text{loss}$
$\Delta N = NT2 - NT1$ = Transformed nitrogen

Table 2. Precipitation in inches during the growing season at the DREC ranch, 2013 and 2014.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season
2013								
inches/month	1.05	7.55	2.23	2.13	2.81	2.44	3.35	21.56
% of LTM	73.43	274.55	68.83	90.64	144.10	169.44	248.15	148.48
wet/dry		wet			wet	wet	wet	wet
2014								
inches/month	1.41	3.73	3.38	0.37	8.84	1.03	0.59	19.35
% of LTM	98.60	135.64	104.32	15.74	453.33	71.53	43.70	133.26
wet/dry		wet		dry	wet	dry	dry	wet
2013-2014								
inches/month	1.23	5.64	2.81	1.25	5.83	1.74	1.97	20.46
% of LTM	86.01	205.09	86.57	53.19	298.72	120.49	145.93	140.87
wet/dry		wet		dry	wet		wet	wet

Table 3. Mean inches of soil water at incremental depths during the growing season on the silty ecological sites of the three grazing management treatments, 2013-2014.

Soil Depth (inches)	Apr	May	Jun	Jul	Aug	Sep	Oct
Nongrazed							
0-6	1.27	1.21	0.66	0.60	0.84	0.92	1.02
6-12	0.91	0.91	0.64	0.43	0.62	0.73	0.81
12-24	1.59	1.42	1.37	0.94	1.15	1.32	1.45
24-36	2.02	1.81	1.73	1.48	1.47	1.43	1.75
36-48	1.74	1.68	1.64	1.40	1.40	1.39	1.49
0-48	7.53	7.03	6.04	4.85	5.48	5.79	6.52
Seasonlong							
0-6	1.43	1.55	1.12	0.83	1.13	0.94	1.34
6-12	1.08	1.05	0.93	0.71	0.82	0.71	1.01
12-24	2.25	2.16	2.16	1.66	1.54	1.39	1.92
24-36	1.53	2.02	2.23	2.13	1.42	1.45	1.91
36-48	1.85	1.86	2.03	2.06	1.25	1.63	1.66
0-48	8.14	8.63	8.45	7.37	6.14	6.10	7.83
Twice-over							
0-6	1.61	1.34	1.19	0.99	1.38	1.17	1.56
6-12	1.37	1.28	1.17	0.86	1.07	1.15	1.34
12-24	2.77	2.53	2.51	1.82	2.14	2.09	2.46
24-36	1.52	2.28	2.52	1.99	2.00	1.99	2.12
36-48	1.39	2.00	2.58	2.18	1.92	2.01	2.03
0-48	8.66	9.43	9.95	7.83	8.52	8.39	9.49

Table 4. Native grass herbage biomass in lbs/ac during the growing season on the silty ecological sites of three grazing management treatments, 2013-2014.

Grazing Management Year	May	Jun	Jul	Aug	Sep	Oct
Nongrazed						
2013	1036.50		2211.57			3226.66
2014	802.21		2870.46			3264.72
Mean	919.36		2541.02			3245.69
Seasonlong						
2013	522.36		1401.63			1212.53
2014	458.84	910.74	1976.08	1019.26	1658.53	1697.18
Mean	490.60	910.74	1688.86	1019.26	1658.53	1454.86
Twice-over						
2013	469.01	1177.20	2030.79	1935.44	2030.19	1754.27
2014	784.48	1310.05	2453.99	1658.53	2642.10	2167.84
Mean	626.75	1243.63	2242.39	1796.99	2336.15	1961.06

Table 5. Mean annual domesticated and native grass herbage biomass (lbs/ac) and basal cover (%) on the silty ecological sites of the three grazing management treatments, 2013-2014.

	Domesticated Grass		Native Grass	
Management Treatment	Herbage lbs/ac	Basal Cover %	Herbage lbs/ac	Basal Cover %
Nongrazed	-	0.17	2235.36	9.64z
Seasonlong	-	0.00	1346.45	22.23y
Twice-over	-	0.37	1916.04	28.30x

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

Table 6. Rhizosphere volume in cubic centimeters per cubic meter of soil (cm^3/m^3), 2002.

Grazing Management	May	Jun	Jul	Aug	Sep	Oct
Nongrazed		1725.24a	2804.61a	2391.97b	2438.47b	
Seasonlong		1800.93a	642.21b	1963.02b	1802.97b	
Twice-over		3214.75a	3867.54a	7183.27a	6586.06a	

Means in the same column and followed by the same letter are not significantly different ($P<0.05$).
Data from Gorder, Manske, and Stroh, 2004.

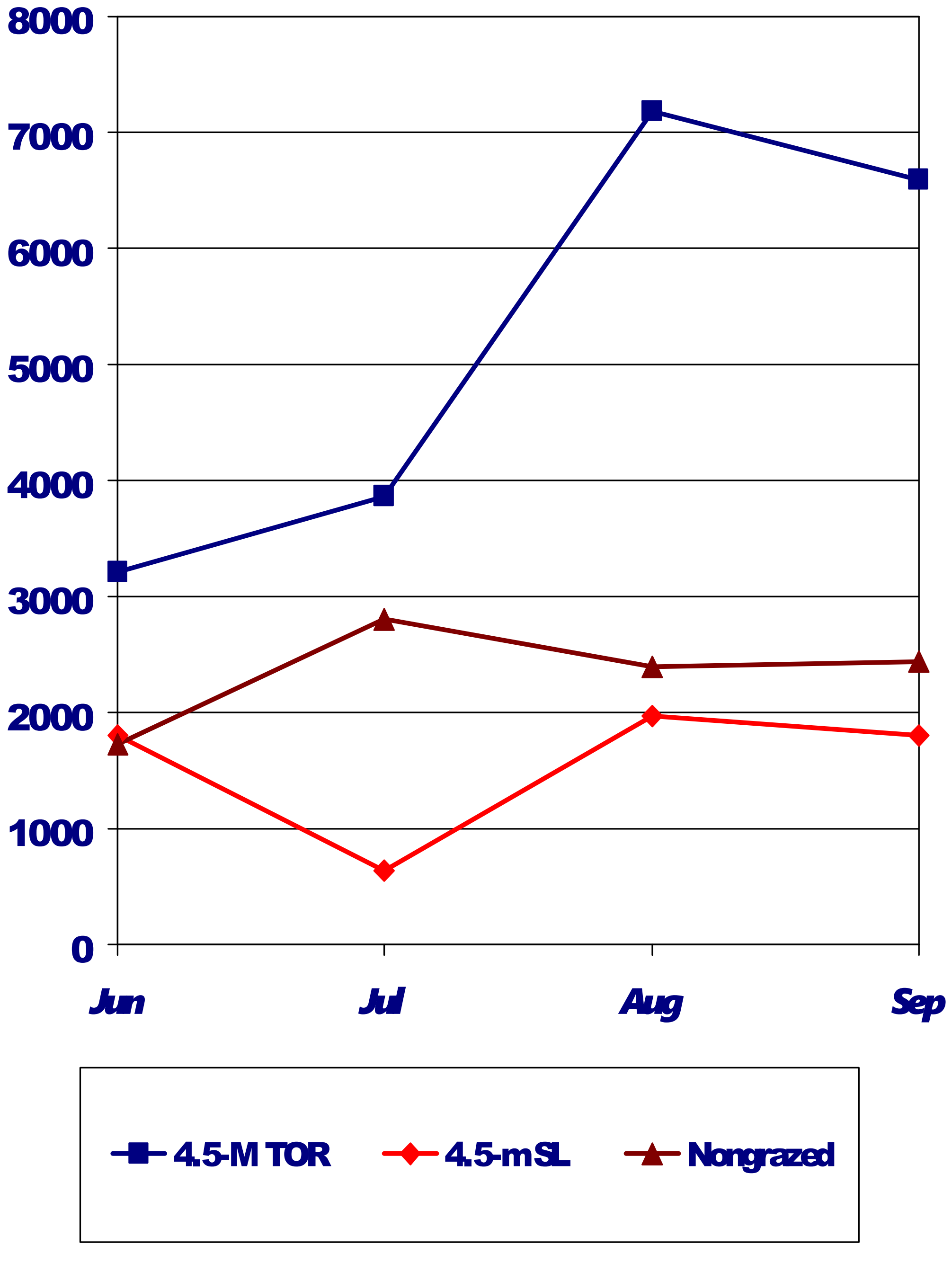

Figure 1. Rhizosphere volume (cm^3) per cubic meter of soil

Table 7. Generalized soil bulk density and soil weight at incremental depths on silty ecological sites of rangeland in southwestern North Dakota.

Soil Depth	Soil Bulk Density	Soil Weight	
(inches)	(g/cm^3)	(lbs/ac)	(tons/ac)
0-6	1.15	1,560,194.37	780.10
6-12	1.30	1,763,697.98	881.85
12-24	1.30	3,536,678.58	1,768.34
24-36	1.33	3,618,294.24	1,809.15
36-48	1.47	3,999,167.32	1,999.58
0-48		14,478,032.49	7,239.02

Average silty soil bulk density from Anonymous. circa early 1980's.
NDSU Soils Department.

Table 8. Soil organic matter (SOM) at incremental depths as percent, pounds per acre, and tons per acre during June on silty ecological sites of the grazing management treatments, 2013-2014.

	Soil Depth (inches)					
	0-6	6-12	12-24	24-36	36-48	0-48
Nongrazed						
SOM						
%	3.08	1.89	1.45	1.15	0.98	1.47
lbs/ac	48,053.99	33,333.89	51,281.84	41,610.38	39,191.84	213,471.94
tons/ac	24.03	16.67	25.64	20.81	19.60	106.74
Seasonlong						
SOM						
%	6.07	3.38	2.55	2.26	2.04	2.82
lbs/ac	94,703.80	59,612.99	90,185.30	81,773.45	81,583.01	407,858.55
tons/ac	47.35	29.81	45.09	40.89	40.79	203.93
Twice-over						
SOM						
%	5.98	4.19	3.38	2.56	2.09	3.20
lbs/ac	93,299.62	73,898.95	119,539.74	92,628.33	83,582.60	462,949.24
tons/ac	46.65	36.95	59.77	46.31	41.79	231.47

Table 9. Soil organic carbon (SOC) at incremental depths as percent, pounds per acre, and tons per acre during June on silty ecological sites of the grazing management treatments, 2013-2014.

	Soil Depth (inches)					
	0-6	6-12	12-24	24-36	36-48	0-48
Nongrazed						
SOC						
%	1.79	1.10	0.84	0.67	0.57	0.86
lbs/ac	27,927.48	19,400.68	29,708.10	24,242.57	22,795.25	124,074.08
tons/ac	13.96	9.70	14.85	12.12	11.40	62.04
Seasonlong						
SOC						
%	3.52	1.96	1.48	1.31	1.18	1.63
lbs/ac	54,918.84	34,568.48	52,342.84	47,399.65	47,190.17	236,419.98
tons/ac	27.46	17.28	26.17	23.70	23.60	118.21
Twice-over						
SOC						
%	3.47	2.43	1.96	1.48	1.21	1.85
lbs/ac	54,138.74	42,857.86	69,318.90	53,550.75	48,389.92	268,256.17
tons/ac	27.07	21.43	34.66	26.78	24.19	134.13

Table 10. Soil organic nitrogen (SON) at incremental depths as percent, pounds per acre, and tons per acre during June on silty ecological sites of the grazing management treatments, 2013-2014.

	Soil Depth (inches)					
	0-6	6-12	12-24	24-36	36-48	0-48
Nongrazed						
SON						
%	0.179	0.110	0.084	0.067	0.057	0.086
lbs/ac	2,792.74	1,940.07	2,970.81	2,424.26	2,279.53	12,407.41
tons/ac	1.40	0.97	1.49	1.21	1.14	6.20
Seasonlong						
SON						
%	0.352	0.196	0.148	0.131	0.118	0.163
lbs/ac	5,491.88	3,456.85	5,234.28	4,739.97	4,719.02	23,642.00
tons/ac	2.75	1.73	2.62	2.37	2.36	11.82
Twice-over						
SON						
%	0.347	0.243	0.196	0.148	0.121	0.185
lbs/ac	5,413.87	4,285.79	6,931.89	5,355.08	4,838.99	26,825.62
tons/ac	2.71	2.14	3.47	2.68	2.42	13.41

Table 11. 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 long-term nongrazed prairie, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	9.75	5.00	2.25	3.13	5.50	3.13
0-6 Transformed		-4.75	-7.50	-6.62	-4.25	-6.62
6-12 Available	3.00	2.38	2.00	2.25	2.25	2.25
6-12 Transformed		-0.62	-1.00	-0.75	-0.75	-0.75
12-24 Available	3.50	2.88	2.00	2.50	4.50	3.50
12-24 Transformed		-0.62	-1.50	-1.00	+1.00	0.00
0-24 Available	16.25	10.26	6.25	7.88	12.25	8.88
0-24 Transformed		-5.99	-10.00	-8.37	-4.00	-7.37
NH_4 ammonium						
0-6 Available	16.48	13.42	12.85	11.06	12.97	15.46
0-6 Transformed		-3.06	-3.63	-5.42	-3.51	-1.02
6-12 Available	13.10	12.45	12.36	13.18	13.87	15.05
6-12 Transformed		-0.65	-0.74	+0.08	+0.77	+1.95
12-24 Available	12.57	12.65	14.68	9.87	12.65	13.38
12-24 Transformed		+0.08	+2.11	-2.70	+0.08	+0.81
0-24 Available	42.15	38.52	39.89	34.11	39.49	43.89
0-24 Transformed		-3.63	-2.26	-8.04	-2.66	+1.74
$NO_3 + NH_4$						
0-6 Available	26.23	18.42	15.10	14.19	18.47	18.59
0-6 Transformed		-7.81	-11.13	-12.04	-7.76	-7.64
6-12 Available	16.10	14.83	14.36	15.43	16.12	17.30
6-12 Transformed		-1.27	-1.74	-0.67	+0.02	+1.20
12-24 Available	16.07	15.53	16.68	12.37	17.15	16.88
12-24 Transformed		-0.54	+0.61	-3.70	+1.08	+0.81
0-24 Available	58.40	48.78	46.14	41.99	51.74	52.77
0-24 Transformed		-9.62	-12.26	-16.41	-6.66	-5.63

Table 12. 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 seasonlong grazing system, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	19.38	12.88	3.25	6.32	6.42	4.57
0-6 Transformed		-6.50	-16.13	-13.06	-12.96	-14.81
6-12 Available	7.57	7.38	3.07	2.76	4.63	2.32
6-12 Transformed		-0.19	-4.50	-4.81	-2.94	-5.25
12-24 Available	10.16	9.00	3.25	5.00	4.75	4.25
12-24 Transformed		-1.16	-6.91	-5.16	-5.41	-5.91
0-24 Available	37.11	29.26	9.57	14.08	15.80	11.14
0-24 Transformed		-7.85	-27.54	-23.03	-21.31	-25.97
NH_4 ammonium						
0-6 Available	18.87	17.32	14.34	14.46	14.42	17.18
0-6 Transformed		-1.55	-4.53	-4.41	-4.45	-1.69
6-12 Available	14.59	15.77	13.81	13.24	13.77	16.62
6-12 Transformed		+1.18	-0.78	-1.35	-0.82	+2.03
12-24 Available	15.37	15.24	13.42	13.91	12.72	14.77
12-24 Transformed		-0.13	-1.95	-1.46	-2.65	-0.60
0-24 Available	48.82	48.32	41.57	41.61	40.91	48.57
0-24 Transformed		-0.50	-7.25	-7.21	-7.91	-0.25
$NO_3 + NH_4$						
0-6 Available	38.24	30.19	17.59	20.78	20.84	21.74
0-6 Transformed		-8.05	-20.65	-17.46	-17.40	-16.50
6-12 Available	22.15	23.14	16.87	15.99	18.39	18.94
6-12 Transformed		+0.99	-5.28	-6.16	-3.76	-3.21
12-24 Available	25.53	24.24	16.67	18.91	17.48	19.02
12-24 Transformed		-1.29	-8.86	-6.62	-8.05	-6.51
0-24 Available	85.92	77.57	51.13	55.68	56.71	59.70
0-24 Transformed		-8.35	-34.79	-30.24	-29.21	-26.22

Table 13. 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 twice-over rotation system, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6 Available	20.94	10.94	2.44	4.25	7.13	3.63
0-6 Transformed		-10.00	-18.50	-16.69	-13.82	-17.32
6-12 Available	9.13	6.50	2.07	2.57	3.94	2.25
6-12 Transformed		-2.63	-7.07	-6.57	-5.19	-6.88
12-24 Available	13.30	11.63	2.00	4.75	3.75	3.50
12-24 Transformed		-1.67	-11.30	-8.55	-9.55	-9.80
0-24 Available	43.37	29.07	6.51	11.57	14.82	9.38
0-24 Transformed		-14.30	-36.86	-31.80	-28.55	-33.99
NH_4 ammonium						
0-6 Available	22.25	18.46	14.48	16.22	15.48	18.09
0-6 Transformed		-3.79	-7.77	-6.03	-6.77	-4.16
6-12 Available	18.03	18.32	15.20	15.26	15.81	19.83
6-12 Transformed		+0.29	-2.83	-2.77	-2.22	+1.80
12-24 Available	18.93	20.46	14.20	16.89	15.22	16.97
12-24 Transformed		+1.53	-4.73	-2.04	-3.71	-1.96
0-24 Available	59.21	57.23	43.88	48.37	46.51	54.89
0-24 Transformed		-1.98	-15.33	-10.84	-12.70	-4.32
$NO_3 + NH_4$						
0-6 Available	43.19	29.40	16.92	20.47	22.61	21.72
0-6 Transformed		-13.79	-26.27	-22.72	-20.58	-21.47
6-12 Available	27.15	24.82	17.26	17.82	19.75	22.08
6-12 Transformed		-2.33	-9.89	-9.33	-7.40	-5.07
12-24 Available	32.23	32.08	16.20	21.64	18.97	20.47
12-24 Transformed		-0.15	-16.03	-10.59	-13.26	-11.76
0-24 Available	102.57	86.29	50.38	59.93	61.33	64.27
0-24 Transformed		-16.28	-52.19	-42.64	-41.24	-38.30

Table 14. 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 three grazing management treatments, 2013-2014.

	Nongrazed		Seasonlong		Twice-over	
Soil Depth (inches)	May Available	Mean Monthly Transformed	May Available	Mean Monthly Transformed	May Available	Mean Monthly Transformed
NO_3 nitrate						
0-6	9.75	-5.45	19.38	12.69	20.94	15.27
6-12	3.00	-0.77	7.57	3.54	9.13	5.67
12-24	3.50	-0.42	10.16	4.91	13.30	8.17
0-24	16.25	-7.15	37.11	21.14	43.37	29.10
NH_4 ammonium						
0-6	16.48	-3.33	18.87	3.33	22.25	5.70
6-12	13.10	+0.28	14.59	+0.05	18.03	1.15
12-24	12.57	+0.08	15.37	1.36	18.93	2.18
0-24	42.15	-2.98	48.82	4.62	59.21	9.03
NO_3 + NH_4						
0-6	26.23	-9.28	38.24	16.01	43.19	20.97
6-12	16.10	-0.49	22.15	3.48	27.15	6.80
12-24	16.07	-0.35	25.53	6.27	32.23	10.36
0-24	58.40	-10.12	85.92	25.76	102.57	38.13

Table 15. 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 three grazing management treatments, 2013-2014.

Soil Depth (inches)	Nongrazed	Seasonlong	Twice-over
NO_3 nitrate			
0-6 Available	4.79	8.80	8.22
0-6 Transformed	-5.95	-12.69	-15.27
6-12 Available	2.36	4.62	4.41
6-12 Transformed	-0.77	-3.54	-5.67
12-24 Available	3.15	6.07	6.49
12-24 Transformed	-0.42	-4.91	-8.17
0-24 Available	10.30	19.49	19.12
0-24 Transformed	-7.15	-21.14	-29.10
NH_4 ammonium			
0-6 Available	13.71	16.10	17.50
0-6 Transformed	-3.33	-3.33	-5.70
6-12 Available	13.34	14.63	17.08
6-12 Transformed	+0.28	+0.05	-1.15
12-24 Available	12.63	14.24	17.11
12-24 Transformed	+0.08	-1.36	-2.18
0-24 Available	39.68	44.97	51.68
0-24 Transformed	-2.98	-4.62	-9.03
NO_3 + NH_4			
0-6 Available	18.50	24.90	25.72
0-6 Transformed	-9.28	-16.01	-20.97
6-12 Available	15.69	19.25	21.48
6-12 Transformed	-0.49	-3.48	-6.80
12-24 Available	15.78	20.31	23.60
12-24 Transformed	-0.35	-6.27	-10.36
0-24 Available	49.97	64.45	70.80
0-24 Transformed	-10.12	-25.76	-38.13

Table 16. Mean cow and calf weight performance (in pounds) on native grassland pastures managed by the seasonlong and the twice-over rotation grazing treatments, 1983-2003.

	Seasonlong		Twice-over	
	Cow	Calf	Cow	Calf
Accumulated Wt	47.77	307.54	86.80	350.33
Gain/Day	0.29	2.42	0.67	2.76
Gain/Acre	3.06	26.19	8.68	35.03

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