Initial Restoration Changes of Degraded Rangeland with the Twice-over Rotation Grazing Strategy

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Biogeochemical processes are the processes that renew nutrient flow activities in ecosystem soils of renewable natural resources. The biogeochemical processes of rangeland natural resources managed with traditional management practices are impeded from functioning at potential levels. Traditional practices that: 1. start grazing too early, before the 3.5 new leaf stage; 2. remove greater than 25% to 33% of green leaf biomass before the flower stage; 3. start grazing too late, after the flower stage; 4. remove greater than 50% of green leaf biomass after peak aboveground herbage biomass produced in late July; 5. continue grazing carryover tillers, after mid October; or 6. “rest” vegetation with nondefoliation during parts or entire growing seasons to increase seed production; are detrimental to the ecosystem biogeochemical processes and are antagonistic to the native plants and soil organisms causing degradation of rangeland renewable natural resources.

Traditional management practices also diminish the compensatory physiological processes, the vegetative reproduction mechanisms, and the rhizosphere organism population (Manske 2011). Decreases in vegetative reproduction by tillering and reductions of compensatory physiological processes prevent grass tillers from replacing a sufficient proportion of the leaf area removed by partial defoliation. Low leaf surface area reduces the quantity of carbon fixed by photosynthesis. Decreases in rhizosphere organism biomass and activity result in decreased biogeochemical processes of the nitrogen cycle causing reductions in the quantity of organic nitrogen converted into mineral nitrogen (Manske 2007). Decreases in the availability of the quantity of fixed carbon and the quantity of mineral nitrogen in an ecosystem degrade grassland plant communities by causing reductions in grass herbage biomass production and native plant density, creating larger and more numerous open spaces between grass plants. These open spaces in the plant communities provide ideal habitat for growth of opportunistic “weedy” plant species that are not dependent on the nitrogen converted by rhizosphere organisms (Manske 2011). Opportunistic grasses and forbs are not highly competitive and do not increase into plant communities unless openings are created by management caused reductions in native grass densities. Degraded grassland ecosystems have an increasing composition of opportunistic introduced grasses, early succession and weedy forbs, and shrubs (Manske 2007).

This project will describe and evaluate development of biological restoration of degraded rangeland resources through implementation of biological effective grazing management. Quantitative annual changes of aboveground herbage biomass, plant species basal cover, forb density, rhizosphere biomass, and available soil mineral nitrogen will document progress of rangeland ecosystem restoration.

Study Area

Restoration research was conducted during 2006 to 2011 on 1,988 acres (804.5 hectares) of degraded native rangeland located about 2 miles (3.22 kilometers) east of the town of Richardton, eastern Stark County in western North Dakota, between 47° 00' and 46° 50' north latitude and between 102° 20' and 102° 10' west longitude.

The untilled rangelands with native plant ecosystems became severely degraded by traditional management practices that were antagonistic to native plant and soil rhizosphere organism biological requirements and to ecosystem biogeochemical processes causing great decreases in the native plant density and herbage biomass. The degraded rangelands subsequently became invaded with undesirable introduced cool season domesticated grasses, primarily kentucky bluegrass with smaller areas of smooth bromegrass and crested wheatgrass, that caused additional problems of shading and increased mulch biomass.

Regional Climatic Factors

The western North Dakota region near Richardton has cold winters and hot summers typical of continental climates. Mean annual temperature is

43.0° F (6.1° C). January is the coldest month, with a mean temperature of 13.5° F (-10.3° C). July and August are 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 is 17.78 inches (451.61 mm). The precipitation during the perennial plant growing season (April through October) is 14.79 inches (375.67 mm) and is 83.2% of the annual precipitation. June has the greatest monthly precipitation, at 3.39 inches (86.11 mm). The precipitation received during the three month period of May, June, and July is 8.15 inches (207.01 mm) and is 45.8% of the annual precipitation.

Water stress develops in perennial plants during water deficiency periods when the amount of rainfall is less than evapotranspiration demand. Water deficiency months were identified from historical temperature and precipitation data by the ombrothermic diagram technique (Emberger et al. 1963). The long-term (1971-2000) ombrothermic diagram shows near water deficiency conditions during August, September, and October, and favorable water relations during April, May, June, and July. Reoccurrence of water deficiency conditions during April, May, June, and July is 16.9%, 13.6%, 10.2%, and 38.1%, respectively, and during August, September, and October water deficiency reoccurs 52.5%, 50.0%, and 46.6% of the years, respectively. Long-term occurrence of water deficiency conditions is 32.7% of the growing season months, for a mean of 2.0 water deficient months per growing season (Manske et al. 2010).

Mean growing season precipitation during the six years of the study was 12.31 inches (83.23% of LTM). During the first three years, growing season precipitation was 9.42, 10.75, and 11.45 inches, respectively, with a mean of 10.54 inches (71.26% of LTM). During the last three years, growing season precipitation was 11.63, 13.43, and 17.15 inches, respectively, with a mean of 14.07 inches (95.13% of LTM) (table 1).

Grazing Management

Restoration of native mixed grass prairie ecosystem biogeochemical processes and plant species composition on degraded rangeland requires implementation of a biologically effective grazing management strategy that activates the defoliation resistance mechanisms and ecosystem biogeochemical processes (Manske 2011). These mechanisms are: compensatory internal physiological processes, internal vegetative reproduction of secondary tillers from axillary buds, and external symbiotic rhizosphere organism activity (McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995; Manske 1999, 2011). The defoliation resistance mechanisms accelerate growth rates of replacement roots, leaves, and shoots, increase photosynthetic capacity of remaining mature leaves, increase allocation of carbon and nitrogen, increase secondary tiller development from axillary buds, and increase conversion of soil organic nitrogen into plant usable mineral nitrogen (Manske 2011).

The twice-over rotation grazing management strategy was the biologically effective management practice implemented to restore the degraded mixed grass prairie biogeochemical processes and native plant communities. During 2006 to 2011, three grassland pastures were grazed from early June until mid October, with each pasture grazed for two periods. A fourth pasture was not grazed and was used as a control. Each of the three pastures in the rotation was grazed for 14 to 16 days during the first period, the 45 day interval from 1 June to 15 July, during which the defoliation resistance mechanisms can be activated by partial defoliation by grazing (Manske 1999, 2011). The length of the first period on each pasture was the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture (Manske 2000). 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. The first pasture grazed in the rotation sequence was the last pasture grazed the previous year.

The stocking rate on the study area was assessed using recently updated ecological site maps and determined that a total of 789.90 AUM's of forage was available on the 1,519 acres of the three grazed pastures. With a grazing season of 4.5 months from early June to mid October, 175 AU's with a total herd weight of 175,533 pounds could graze at a stocking rate of 1.92 ac/AUM. The intended stocking rates were to graze at 75%, 85%, and 95% of the assessed stocking rate during years 1, 2, and 3, respectively, and thereafter to graze at slightly less than 100% of the assessed stocking rate for the duration of the study. The actual stocking rates used during the study were a little different than the intended stocking rates. Heavy weight livestock (1450 lbs mean weight) grazed at 72.3%, 82.6%, and 107.5% of the assessed stocking rate during years 1, 2, and 3, respectively. Medium weight livestock (900 lbs mean weight) grazed at 79.8% and 87.4% of the assessed stocking rate during years 4 and 5, respectively. Light weight livestock (650 lbs mean weight) grazed at 37.8% of the assessed stocking rate during year 6.

The twice-over rotation grazing management strategy coordinates defoliation by grazing with grass phenological growth stages which improves plant health and activates biological and ecological processes within grass plants and the ecosystem so that beneficial changes to plant growth, rhizosphere organisms, and biogeochemical cycles in the ecosystem result (Manske 2000). During the first grazing period, grass lead tillers are between the three and a half new leaf stage and the flower (anthesis) stage; these are the vegetative stages of tiller development at which partial defoliation by grazing produces beneficial effects by activating the defoliation resistance mechanisms that increase compensatory growth rates, increase tillering from axillary buds, and enhance activity of rhizosphere organisms. Increased compensatory growth rates replace leaf and stem material at greater quantities than that removed by grazing substantially increasing the amounts of herbage biomass production. Increased vegetative reproduction by tillering contributes to the development of greater plant basal cover and to the production of greater grass herbage weight. Increased activity of the soil organisms in the rhizosphere supplies the plant with greater quantities of essential nutrients, primarily mineral nitrogen, to support additional growth (Manske 2000, 2011). Removal of livestock from native rangeland pastures in mid October, towards the end of the perennial grass growing season, allows grass plants to store carbohydrates and nutrients needed to maintain plant processes over the winter that will retain the fall vegetative tiller growth and the other carryover tillers which become next season's tillers (Manske 2003, 2011). The twice-over grazing strategy ensures healthy plants in the spring and greater herbage production during the next growing season (Manske 2000, 2011).

Renewable natural resources are complex ecosystems with several trophic layers of living organisms that have biological requirements, and with numerous nonliving components that have characteristics that are transformable between organic and inorganic forms. Management of renewable natural resources needs to meet all the requirements of the living and nonliving components of the ecosystem for the purpose of improving the biogeochemical processes and maintaining production at potential sustainable levels.

Continued ecosystem production at potential sustainable levels of rangeland and grassland renewable natural resources requires that management meets the biological requirements of the plants and soil organisms. The ecosystem biogeochemical processes and the organism physiological mechanisms that provide the biological requirements for grassland plants and rhizosphere organisms must be activated annually with partial defoliation by large graminivores during vegetative growth stages. Grazing animals are a necessity for full functionality of grassland plants and rhizosphere organisms.

Performance of the defoliation resistance mechanisms and biogeochemical processes ensure healthy productive native grass plants, active rhizosphere organisms, and fully functioning mixed grass prairie ecosystems. Activation of the mechanisms and processes result in increased herbage biomass production, increased plant density (basal cover), increased available forage nutrients, increased soil aggregation, improved soil quality, increased soil water holding capacity, increased resistance to drought conditions, improved wildlife habitat, improved grassland aesthetics, and improved grassland ecosystem quality (Manske 2011).

Procedures

The effects from a biologically effective grazing management strategy in the restoration of native mixed grass prairie ecosystem biogeochemical processes and grassland plant species composition on degraded untilled rangeland were evaluated in four pastures on silty ecological sites with permanent sample plots organized in a paired-plot design. A 16' X 32' (4.88 m X 9.75 m) stock panel exclosure prevented livestock access to an ungrazed plot. A grazed plot on an adjacent area of equal size was accessible by livestock. Ungrazed and grazed plots were established at each reference site for nondestructive data collection. An additional area of similar size accessible by livestock was established at each reference site for destructive data collection. Ecosystem changes in aboveground herbage biomass, plant species basal cover, forb density, and rhizosphere biomass were evaluated with data collected from late May through mid October during six growing seasons, 2006 to 2011. The plant basal cover and forb density data were collected along permanent transect lines established at each nondestructive sample site both inside (ungrazed) and outside (grazed) each exclosure. The major transect lines were parallel to each other on opposite sides of the exclosure fence. The minor transect lines were perpendicular to the major transect lines and were parallel to each other.

Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986) at each pasture rotation date, with seven clip periods per year. The herbage material from five 0.25 m^2 quadrats (frames) at each destructive sample site outside (grazed) each exclosure was hand clipped to ground level and sorted in the field by biotype categories: domesticated grasses, cool season grasses, warm season grasses, upland 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. Mean monthly herbage biomass for each category were determined for each growing season. Relative composition of herbage biomass biotype categories were determined.

Plant species basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986), with 2000 points collected along permanent transect lines during peak growth between mid July and mid August. Basal cover plant species data were sorted into biotype categories: domesticated grasses, cool season grasses, warm season grasses, upland sedges, forbs, and litter. Percent basal cover and relative composition of basal cover for the biotype categories were determined from the ten-pin point frame data.

Density of forbs were determined by counting individual stems of each plant species rooted inside twenty five 0.1 m^2 quadrats placed along permanent transect lines between mid July and mid August. Forb species were categorized as: late succession, mid succession, and early succession forbs. Density per 0.1 m^2 and relative composition of forb categories were determined from the forb density data.

Rhizosphere biomass was collected at each destructive sample site outside (grazed) each exclosure by three replicated soil cores 3 inches (7.6 cm) in diameter and 4 inches (10.2 cm) in depth 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.

Soil mineral nitrogen, nitrate and ammonium, was sampled towards the end of the sixth grazing season from both inside (ungrazed) and outside (grazed) each exclosure by three replicated soil cores with 6 inch (15.2 cm) increments to a 12 inch (30.5 cm) depth collected using a Veihmeyer soil tube with 1 inch (2.5 cm) diameter. Soil cores were placed on ice immediately and were frozen within 2 to 3 hours of collection. 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. Total available mineral nitrogen at a one foot depth was determined from the soil core data and reported as pounds per acre.

Interpretation of treatment effects on plant community characteristics assumes only minor differences in the vegetation of the grazed area and ungrazed area at the time of exclosure construction on each reference site. A standard t-test was used to analyze differences among means (Mosteller and Rourke 1973). Nomenclature of plant species follows Flora of the Great Plains (1986).

Results

Effects of Previous Management

The mixed grass prairie ecosystems on the study area degraded because the previous management was designed for the intended “use” and did not meet the biological requirements of the perennial native grass plants and the rhizosphere organisms and was detrimental to the biogeochemical processes. The use of rangeland natural resources should not be the objective of management. The management should be the means to accomplish the uses.

Ecosystem processes functioned at some degree less than potential level each growing season that the rangeland was managed with traditional concepts based on a use. Soon after the first ecosystem process failed to function properly, the other belowground processes and mechanisms began to deteriorate. The native grass live root biomass decreased (Whitman 1974), the defoliation resistance mechanisms within grass plants diminished, the ecosystem biogeochemical processes declined, and the competitiveness of grass plant resource uptake deteriorated (Manske 2011).

The reduction of live root surface area caused a decrease in active root length for interaction with symbiotic rhizosphere organisms and caused a decrease in absorption of water and nutrients from the soil. Reduction of active root biomass and diminishment of grass plant health vigor resulted in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water (Li and Wilson 1998, Kochy 1999, Kochy and Wilson 2000, Peltzer and Kochy 2001). The loss of active root length was a contributing factor in the reduction of rhizosphere biomass. The primary cause for the reduction in rhizosphere biomass was, however, the great reduction in the quantity of carbohydrates exuded from the grass roots into the rhizosphere zone. The antagonistic traditional practices greatly reduced the quantity of short carbon chain energy exuded from the grass roots into the rhizosphere; this low amount of simple carbon compounds was not enough to sustain an adequate rhizosphere biomass. The small biomass of rhizosphere organisms mineralized small quantities of nitrogen and other essential elements (Coleman et al. 1983, Klein et al. 1988).

The decreased amounts of available mineral nitrogen below 100 lbs/ac in the ecosystem caused reductions in native grass herbage biomass production (Wight and Black 1972, 1979) and caused decreases in native grass density (basal cover). As degradation continued, numerous bare spaces between native grass plants were created in the plant communities. The open spaces were ideal habitat for growth of opportunistic domesticated grass species. The composition of grass species changed with decreases in the desirable native species and increases in the less desirable domesticated species.

Standing dead leaves accumulated (Brand and Goetz 1986) as ecosystem deterioration progressed. The accumulation of live and standing dead leaves of domesticated grasses reduced light penetration greatly. Reduced sunlight to native grasses caused reduced rates of photosynthesis, decreased rates of herbage production, and increased rates of leaf senescence (Langer 1972, Briske and Richards 1995) decreasing native grass composition further. Great quantities of standing dead material did not make contact with soil preventing decomposition through microbial activity and causing litter to build up into a thick mulch layer. The thick mulch modified soil temperatures, inhibited water infiltration, and tied up carbon and nitrogen (Wright and Bailey 1982; Manske 2000, 2011). Native grasses were further inhibited by deficiencies of soil water, cool soil temperatures during spring, and reduced ecosystem nutrients caused by thick mulch.

The change in plant composition from desirable native grasses to less desirable domesticated grasses was the visible symptom of ecosystem degradation; the fundamental degradation of the ecosystem was the reduction of rhizosphere biomass, the reduction of biogeochemical processes, the reduction of available mineral nitrogen below 100 lbs/ac, and the reduction of all the other essential elements. The degree of the aboveground plant species deterioration lagged behind the degree of degradation of the belowground ecosystem processes and mechanisms (Manske 2011).

There is a major fundamental problem with traditional concepts that manage renewable natural resources from the perspective of their use or for the product removed. Management of renewable resources for a use narrowly considers only a few factors directly related to that use or product, and neglects to address the needs of all the other components required for the ecosystems to function at potential levels. The renewable natural resources (rangelands, grasslands, croplands, forestlands, and fisheries) have all been managed traditionally for their use. The ecosystem processes that renew the renewable natural resources are functioning at subpotential levels. The declining production from the worlds renewable resources is a symptom of degraded ecosystem processes that have resulted from management for a use.

Control Pasture NG

The mixed grass prairie study area in the ungrazed control pasture NG was a degraded silty ecological site dominated by kentucky bluegrass. Control pasture NG was not grazed during the six years of study. At the start of the study (May year 1), 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, 2.5% native grasses (2.0% cool season grasses, 0.4% upland sedges, and less than 0.1% warm season grasses), and 2.4% forbs (tables 2 and 3).

The domesticated grass herbage biomass changed little numerically throughout the study. From a starting biomass of 1684.81 lbs/ac (95.2% composition), the weight decreased (12.8%) to 1468.69 lbs/ac (72.7% composition) during years 1 to 5, and increased (38.5%) to 2333.98 lbs/ac (85.1% composition) during year 6 (tables 2 and 3). The domesticated grass basal cover changed little during the first 4 years, greatly increased during the fifth year, and greatly decreased during the sixth year. The dominant domesticated grass was kentucky bluegrass. From a starting basal cover of 10.55% (71.3% composition), the basal cover increased (123.7%) to 23.60% (83.1% composition) during years 1 to 5, and then decreased to 15.35% (86.0% composition) during year 6 (tables 4 and 5).

The quantity of native cool season grasses was low during the study. The cool season grass herbage biomass increased slightly during the first four years and then decreased during the last two years. From a low starting biomass of 35.68 lbs/ac (2.0% composition), the weight increased (597.1%) to 248.74 lbs/ac (11.1% composition) during years 1 to 4, and then decreased (76.9%) to 57.49 lbs/ac (2.1% composition) during years 5 to 6 (tables 2 and 3). The native cool season grass basal cover increased slightly during the first three years and then decreased during the last three years. The cool season grasses were western wheatgrass, needle and thread, and green needlegrass. From a starting basal cover of 1.20% (8.1% composition), the basal cover increased (195.8%) to 3.55% (20.7% composition) during years 1 to 3, and then decreased (90.1%) to 0.35% (2.0% composition) during years 4 to 6 (tables 4 and 5).

The quantity of native warm season grasses was low during the study. The warm season grass herbage biomass changed little during the study. From an extremely low starting biomass of 0.71 lbs/ac (0.04% composition), the weight increased to 153.73 lbs/ac (5.6% composition) during years 1 to 6 (tables 2 and 3). The native warm season grass basal cover increased slightly during the study. The warm season grass remaining on the ungrazed site was a small remnant colony of prairie sandreed. From an extremely low starting basal cover of 0.05% (0.34% composition), basal cover increased a little to 0.85% (4.8% composition) during years 1 to 6 (tables 4 and 5).

The native cool and warm season grasses changed little during the study. From a low starting biomass of 36.39 lbs/ac (2.1% composition), the weight increased to 304.91 lbs/ac (13.6% composition) during years 1 to 4 and then decreased to 211.22 lbs/ac (7.7% composition) during years 5 to 6 (tables 2 and 3). The total cool and warm season grass basal cover increased slightly during the first three years, and then decreased slightly during the last three years. From a low starting basal cover of 1.25% (0.34% composition), the basal cover increased (216.09%) to 3.95% (23.0% composition) during years 1 to 3, and the decreased (69.6%) to 1.20% (6.7% composition) during years 4 to 6 (tables 4 and 5).

The quantity of upland sedges was low during the study. The upland sedge herbage biomass increased slightly during the first four years and then decreased during the last two years. From a low starting biomass of 7.14 lbs/ac (0.4% composition), the weight increased to 49.44 lbs/ac (2.2% composition) during years 1 to 4, and then decreased to 11.82 lbs/ac (0.4% composition) during years 5 to 6 (tables 2 and 3). The upland sedge basal cover decreased during the study. The upland sedge was primarily threadleaf sedge. From a starting basal cover of 2.85% (19.3% composition), the basal cover decreased (63.2%) to 1.05% (5.9% composition) during years 1 to 6 (tables 4 and 5).

The quantity of forbs was low during the study. The forb herbage biomass decreased during the first three years, increased during the fourth and fifth years, and then decreased during the sixth year. From a low starting biomass of 42.10 lbs/ac (2.4% composition), the weight decreased (35.8%) to 27.02 lbs/ac (1.8% composition) during years 1 to 3, the weight increased (783.2%) to 238.65 lbs/ac (11.8% composition) during years 4 to 5, and the weight decreased (22.3%) to 185.43 lbs/ac (6.8% composition) during year 6 (tables 2 and 3). Forb density decreased during the first three years and increased during the last three years. From a starting density of 5.44 forbs/0.10 m^2, the density decreased (89.7%) to 0.56 forbs/0.10 m^2 during years 1 to 3, and the density increased (535.7%) to 3.56 forbs/0.10 m^2 during years 4 to 6.

Standing dead biomass was 1824.68 lbs/ac (28.6% composition) at the start of the study, decreasing (76.3%) to 432.54 lbs/ac (11.0% composition) during years 1 to 5, and then increasing (184.1%) to 1229.02 lbs/ac (17.2% composition) during year 6. Litter biomass was 2785.89 lbs/ac (43.7% composition) at the start of the study, decreased (47.0%) to 1476.03 lbs/ac (37.6% composition) during years 1 to 5, and then increased (115.4%) to 3178.78 lbs/ac (44.5% composition) during year 6. The litter layer was very thick during each year on the ungrazed control pasture. The biomass of the litter was greater during the sixth year than during the first year. The mean annual litter biomass was 2356.04 lbs/ac (43.4% composition). Total dead biomass (standing dead and litter) was 4610.57 lbs/ac (72.3% composition) at the start of the study, the biomass decreased (58.6%) to 1908.57 lbs/ac (48.6% composition) during years 1 to 5, and then increased (130.9%) to 4407.80 lbs/ac (61.7% composition) during year 6. The mean annual total dead biomass was 3356.59 lbs/ac (61.8% composition).

After 6 growing seasons on the ungrazed control pasture NG, 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, 8.1% native grasses (5.6% warm season grasses, 2.1% cool season grasses, and 0.4% upland sedges), and 6.8% forbs (table 3).

The vegetation on control pasture NG changed slightly during the 6 years of nongrazing management. Domesticated grass herbage biomass increased 38.5% and basal cover increased 45.5%. Cool season grass herbage biomass increased 61.1% and basal cover decreased 70.8%. Warm season grass herbage biomass increased 2155.1% and basal cover increased 1600.0%. Upland sedge herbage biomass increased 65.5% and basal cover decreased 63.2%. Forb herbage biomass increased 340.5% and density decreased 34.6%. Total live herbage biomass increased 54.9% and total live basal cover increased 20.6%. Standing dead herbage biomass decreased 32.6% and litter biomass increased 14.1%.

The total available soil mineral nitrogen was 81.36 lbs/ac. The quantity of nitrate was 10.50 lbs/ac and the quantity of ammonium was 70.86 lbs/ac. The amount of available mineral nitrogen was high, indicating that the level of plant growth was reduced and the rate of available mineral nitrogen use was also reduced. The high quantities of nitrate appear to be related to the greater quantities of easily decomposed labile roots of domesticated grasses. The ungrazed control pasture had high domesticated grass basal cover. The high quantities of ammonium are usually related to greater quantities of native grass roots and greater rhizosphere biomass. However, the ungrazed control pasture had extremely low basal cover of native grasses. The ungrazed control pasture did have high kentucky bluegrass basal cover. It appears that the high quantity of ammonium on the ungrazed control pasture could be related to the easily decomposed labile roots of kentucky bluegrass with low rhizosphere biomass.

The domesticated grasses and native grasses on the ungrazed control pasture responded to water stress at different levels. The amount of precipitation during the first three years was a little less than 75% of the long-term mean resulting in early stages of water stress. The domesticated grasses were under water stress and the herbage biomass production decreased (21.6%) to 1320.16 lbs/ac. The native grasses, however, were not under as much water stress and the reduction of domesticated grass herbage biomass permitted the native grasses to increase production (273.9%) to 162.75 lbs/ac during the first three years with low precipitation.

The amount of precipitation during the last three years was greater at about 95% of the long-term mean. The domesticated grasses were no longer under water stress and the herbage biomass production increased (76.8%) to 2333.98 lbs/ac. The increased domesticated grass herbage biomass increased the shading effect on most of the smaller native grasses and caused a reduction in herbage biomass. However, a small remnant colony of prairie sandreed, a tall native grass, was able to grow above the shading by the domesticated grass leaves and was able to produce some herbage biomass at 223.05 lbs/ac which was an increase of 37.1% greater than the native grass herbage biomass production during the three years with low precipitation.

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

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

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

The decreased supply of soil water, mineral nitrogen, and fixed carbon resulted in a major reduction in assimilation of plant tissue, reducing growth of leaves and roots, and reducing the development of vegetative secondary tillers (Langer 1972, Briske and Richards 1995). Native grass tiller mortality increased and native plant density decreased (Grant et al. 1983), creating large open spaces available for invasion by the less desirable domesticated cool season grasses, kentucky bluegrass and smooth bromegrass. The increasing live herbage biomass and increasing standing dead biomass of the invading domesticated grasses caused additional shading that resulted in accelerated reductions of the native grasses.

Grazed Pastures TOR

The mixed grass prairie study areas in grazed pastures TOR were degraded silty ecological sites dominated by kentucky bluegrass. At the start of the study (May year 1), 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, 26.2% native grasses (22.9% upland sedges, 2.7% cool season grasses, and 0.6% warm season grasses), and 9.0% forbs (table 7).

The domesticated grass herbage biomass decreased during the first and third years, increased slightly during the second, fourth, and fifth years, and increased greatly during the sixth year. From a pregrazing biomass of 1066.48 lbs/ac (64.8% composition), the weight decreased (35.7%) to 685.72 lbs/ac (39.8% composition) during years 1 to 5, and increased (83.9%) to 1261.24 lbs/ac (58.0% composition) during year 6 (tables 6 and 7). The domesticated grass basal cover increased during the first 5 years. The domesticated grasses were primarily kentucky bluegrass with small quantities of smooth bromegrass and crested wheatgrass. From a pregrazing basal cover of 3.45% (24.8% composition), the basal cover increased (99.4%) to 6.88% (22.7% composition) during years 1 to 5 and 6 (tables 8 and 9). Kentucky bluegrass had the greatest basal cover increase.

The native cool season grass herbage biomass increased during the first six years. From a pregrazing biomass of 43.53 lbs/ac (2.7% composition), the weight increased (1090.4%) to 518.18 lbs/ac (23.8% composition) during years 1 to 6 (tables 6 and 7). The native cool season grass basal cover increased during the first five years and then decreased during the sixth year. The primary cool season grasses were western wheatgrass, needle and thread, and prairie junegrass. From a pregrazing basal cover of 1.85% (13.3% composition), the basal cover increased (228.6%) to 6.08% (20.1% composition) during years 1 to 5, and then decreased to 3.93% (16.8% composition) during year 6 (tables 8 and 9).

The native warm season grass herbage biomass increased during the first six years. From a pregrazing biomass of 10.00 lbs/ac (0.6% composition), the weight increased (388.9%) to 48.89 lbs/ac (2.3% composition) during years 1 to 6 (tables 6 and 7). The warm season grass basal cover increased during the first six years. The primary warm season grasses were blue grama, prairie sandreed, and plains muhly. From a pregrazing basal cover of 0.43% (3.1% composition), the basal cover increased (488.4%) to 2.53% (10.8% composition) during years 1 to 6 (tables 8 and 9).

The total native cool and warm season grass herbage biomass increased during the first six years. From a pregrazing biomass of 53.53 lbs/ac (3.3% composition), the weight increased (959.3%) to 567.07 lbs/ac (26.1% composition) during years 1 to 6 (tables 6 and 7). The total native cool and warm season grass basal cover increased during the first five years, and then decreased slightly during the sixth year. From a pregrazing basal cover of 2.28% (16.4% composition), the basal cover increased (236.0%) to 7.66% (25.3% composition) during years 1 to 5, and then decreased (15.7%) to 6.46% (27.6% composition) during year 6 (tables 8 and 9).

The native upland sedge herbage biomass decreased during the first six years. From a pregrazing biomass of 377.14 lbs/ac (22.9% composition), the weight decreased (35.0%) to 245.17 lbs/ac (11.3% composition) during years 1 to 6 (tables 6 and 7). The upland sedge basal cover increased during the first five years, and then decreased during the sixth year. The upland sedge was threadleaf sedge. From a pregrazing basal cover of 7.63% (54.8% composition), the basal cover increased (66.4%) to 12.70% (41.9% composition) during years 1 to 5, and then decreased (24.8%) to 9.55% (40.9% composition) during year 6 (tables 8 and 9).

The forb species composition was dynamic on the grazed pastures. The forb herbage biomass decreased during the first three years, increased greatly during the fourth and fifth years, and then decreased during the sixth year. From a pregrazing biomass of 147.72 lbs/ac (9.0% composition), the weight decreased (76.2%) to 35.17 lbs/ac (4.3% composition) during years 1 to 3, the forb biomass increased (917.5%) to 357.87 lbs/ac (20.8% composition) during years 4 to 5, and then decreased (72.0%) to 100.11 lbs/ac (4.6% composition) during year 6 (tables 6 and 7). Forb density decreased during the first three years and then the densities of blue wild lettuce and yellow sweetclover increased greatly during the last three years. From a pregrazing density of 5.52 forbs/0.10 m^2, the density of the late, mid, and early succession forbs all decreased (76.1%) to a total density of 1.32 forbs/0.10 m^2 during years 1 to 3. The early succession forbs increased greatly by 4666.7% and 4655.6% during years 4 and 6, respectively, resulting in total forb density increases (790.9%) to 11.76 forbs/0.10 m^2 and increases (753.0%) to 11.26 forbs/0.10 m^2 during years 4 and 6, respectively.

Standing dead biomass was 1213.84 lbs/ac (26.9% composition) at the start of the study, the biomass decreased (91.2%) to 107.40 lbs/ac (4.9% composition) during years 1 to 4, and then increased (374.6%) to 509.77 lbs/ac (14.2% composition) during years 5 to 6. Litter biomass was 1661.26 lbs/ac (36.8% composition) at the start of the study, the biomass decreased (71.5%) to 473.94 lbs/ac (18.5% composition) during years 1 to 5, and then increased (89.5%) to 898.17 lbs/ac (25.1% composition) during year 6. The litter layer was not thick after the first year and the litter biomass averaged 825.60 lbs/ac during years 2 to 6. The total dead biomass (standing dead and litter) was 2875.10 lbs/ac (63.6% composition) at the start of the study, the total biomass decreased (75.0%) to 718.19 lbs/ac (32.8% composition) during years 1 to 4, and then increased (96.0%) to 1407.93 lbs/ac (39.3% composition) during years 5 to 6 (tables 6 and 7).

After 6 growing seasons managed with the twice-over rotation system, the aboveground vegetation biomass on grazed pastures TOR consisted of 39.3% standing dead and litter and 60.7% live herbage. The live herbage was 58.0% domesticated grasses, 37.4% native grasses (23.8% cool season grasses, 11.3% upland sedges, and 2.3% warm season grasses), and 4.6% forbs (table 7).

The vegetation on grazed pastures TOR changed for the better during the 6 years of twice-over rotation grazing management. Domesticated grass herbage biomass increased 18.3% and basal cover increased 99.4%. Cool season grass herbage biomass increased 109.0% and basal cover increased 112.4%. Warm season grass herbage biomass increased 388.9% and basal cover increased 488.4%. Upland sedge herbage biomass decreased 35.0% and basal cover increased 25.2%. Forb herbage biomass decreased 32.2% and forb density increased 104.0%. Total live herbage biomass increased 32.1% and total live basal cover increased 67.8%. Standing dead herbage biomass decreased 58.0% and litter biomass decreased 45.9%.

The total available soil mineral nitrogen of nitrate and ammonium was 53.78 lbs/ac on the exclosure and 56.74 lbs/ac on the grazed area, with an increase of 5.5% on the grazed area. The quantity of mineral nitrogen was greater on the grazed area than on the ungrazed exclosure. The quantity of nitrate was 6.84 lbs/ac on the exclosure and 5.67 lbs/ac on the grazed area, with a decrease of 17.1% on the grazed area. The quantity of ammonium was 46.95 lbs/ac on the exclosure and 51.08 lbs/ac on the grazed area, with an increase of 8.8% on the grazed area. The exclosure had greater nitrate and lower ammonium and the grazed area had lower nitrate and greater ammonium. The quantity of nitrate was reduced on both the exclosure and grazed area. Reduced quantities of nitrate appear to be related to reduced quantities of easily decomposed labile roots of domesticated grasses. Both the exclosure and grazed area had reduced domesticated grass basal cover. The grazed area had greater ammonium. The greater quantities of ammonium appear to be related to the greater quantities of native grass roots and greater rhizosphere biomass.

The degraded mixed grass prairie silty ecological sites on grazed pastures TOR were dominated by kentucky bluegrass with 64.8% composition. The native cool and warm season grasses had been reduced to 3.3% composition. These degraded prairie sites were managed with the twice-over rotation system for 6 years. During the first three years, heavy weight livestock with mean weight of 1450 lbs were stocked at 72.3%, 82.6%, and 107.5% of the assessed stocking rate, respectively, and the livestock consumed 394 lbs, 450 lbs, and 585 lbs of herbage weight per acre, respectively. During the first three years, standing dead biomass decreased (65.3%) to 420.37 lbs/ac, litter biomass decreased (32.9%) to 1114.80 lbs/ac, domesticated grass herbage biomass decreased (70.9%) to 310.77 lbs/ac, and total live herbage biomass decreased (49.9%) to 824.67 lbs/ac. The native cool and warm season grasses increased (295.6%) to 211.74 lbs/ac.

The near full stocking rates at a mean of 87.5% of the assessed stocking rate of the heavy weight livestock that consumed a mean of 476 lbs of herbage biomass per acre removed sufficient quantities of domesticated grass and standing dead herbage biomass to substantially reduce the shading problems, permitting sunlight to reach the shorter native grasses. Partial defoliation of the native grasses by grazing livestock during vegetative phenological stages stimulated the defoliation resistance mechanisms, activated the rhizosphere organisms, and enhanced the ecosystem biogeochemical processes resulting in increased herbage biomass production and greater vegetative tiller growth.

The stocking rate at greater than 100% of the assessed value during year 3 caused both beneficial effects and negative effects. The third growing season was the only time that grazing livestock were at great enough quantities to remove 916.93 lbs/ac of domesticated grass and standing dead biomass and open the grass leaf canopy sufficiently. Carryover effects lasted into the following grazing season during year 4. Standing dead biomass decreased (74.5%) to 107.40 lbs/ac and litter biomass decreased (45.2%) to 610.79 lbs/ac. Native cool and warm season grass herbage biomass increased (109.8%) to 444.27 lbs/ac. However, the negative factors were also great, total forb biomass increased (168.7%) to 94.50 lbs/ac and weedy forb density increased 4666.7% during the next growing season as a result of opening the grass canopy excessively and exposing sunlight on large areas of soil causing weed seeds to germinate.

During the fourth and fifth years, medium weight livestock with mean weight of 900 lbs were stocked at 79.8% and 87.4% of the assessed stocking rate, respectively, and the livestock consumed 304 lbs and 333 lbs of herbage weight per acre, respectively. The quantity of herbage biomass consumed per acre was insufficient to maintain ecosystem improvement. Standing dead biomass increased (238.6%) to 363.68 lbs/ac, domesticated grass herbage biomass increased (120.7%) to 685.72 lbs/ac, and forb herbage biomass increased (278.7%) to 357.87 lbs/ac. Native cool and warm season grass herbage biomass decreased (21.9%) to 346.76 lbs/ac.

During the sixth year, light weight livestock with mean weight of 650 lbs were stocked at 37.8% of the assessed stocking rate and the livestock consumed 113 lbs of herbage weight per acre. At this low stocking rate, the quantity of herbage biomass consumed per acre was so inadequate that ecosystem restoration stopped, causing the return of advancements of degradation. Standing dead biomass increased (40.2%) to 509.77 lbs/ac, litter biomass increased (89.5%) to 898.17 lbs/ac, domesticated grass herbage biomass increased (83.9%) to 1261.24 lbs/ac, and early succession forb density increased 256.7%. Native cool and warm season grass herbage biomass increased (63.5%) to 567.07 lbs/ac as a result of continued effects from previous beneficial partial defoliation by grazing at heavier stocking rates.

Differences in Restoration Changes

The restoration changes of the ecosystems on the ungrazed control pasture NG and on the grazed pastures TOR were different. At the start of the study, a similarity index of 52.6% indicated that the degraded plant communities on the ungrazed control pasture NG and on the grazed pastures TOR were more similar than dissimilar.

During the study, the grazing managed with twice-over rotation strategy on pastures TOR reduced the standing dead biomass 58.5% and reduced the litter biomass 71.7% below that on the ungrazed control pasture NG. This reduction in standing dead decreased the problems caused by shading that reduced the rates of photosynthesis and increased the rates of leaf senescence in native grasses. This reduction in litter decreased the problems caused by thick mulch that modified soil temperatures, inhibited water infiltration, and tied up carbon and nitrogen.

During the study, domesticated grass herbage biomass increased 649.17 lbs/ac (38.5%) and basal cover increased 4.80 percentage points (45.5%) on the ungrazed pasture NG. Domesticated grass herbage biomass increased 194.76 lbs/ac (18.3%) and basal cover increased 3.43 percentage points (99.4%) on the grazed pastures TOR. At the end of the study, domesticated grass herbage biomass was 46.0% less and basal cover was 55.2% less on the grazed pastures TOR than on the ungrazed control pasture NG. The rate of increase of domesticated grass herbage biomass and basal cover was restricted by the grazing treatment.

The combined aboveground vegetation biomass of domesticated grass and standing dead caused the shading problem and prevented most of the sunlight from reaching the smaller native grass plants growing in the understory. During the study, the annual mean combined vegetation biomass was 2617.80 lbs/ac on the ungrazed pasture NG and was significantly less at 1277.06 lbs/ac on the grazed pastures TOR. The grazing treatment reduced the shading problem 51.2% which was sufficient to permit greater amounts of sunlight to reach native grass leaves, increasing the photosynthetic rates that increased the quantities of fixed carbon available to native grasses resulting in increased growth rates. The annual mean native grass herbage biomass on the ungrazed pasture NG was only 245.28 lbs/ac and was significantly greater at 650.01 lbs/ac on the grazed pastures TOR. The grazing treatment increased the native grass production 165.0% as a result of reducing the shading problem.

At the end of the study, cool and warm season grass herbage biomass was 168.5% greater and basal cover was 438.3% greater on the grazed pastures than on the ungrazed pasture. Native upland sedge herbage biomass was 1974.2% greater and basal cover was 809.5% greater on the grazed pastures than on the ungrazed pasture. Forb herbage biomass was 46.0% less and forb density was 216.3% greater on the grazed pastures than on the ungrazed pasture.

The improvements of the native grasses in the degraded native mixed grass prairie communities on the grazed pastures TOR indicated that the defoliation resistance mechanisms were activated to some degree by the twice-over rotation grazing management strategy. Increased activity of the compensatory internal physiological growth processes resulted in increased production of native grass herbage biomass. Increased activity of the internal vegetative reproductive processes resulted in increased native grass basal cover. At the end of the study, a similarity index of 37.3% indicated that the improved plant communities on grazed pastures TOR and the degraded plant communities on ungrazed control pasture NG were more dissimilar than similar.

The previous management degraded the plant communities and caused reductions in the quantity of plant carbon exudates released into the rhizosphere that caused a decrease in rhizosphere biomass. At the start of the study, the rhizosphere biomass on ungrazed control pasture NG had decreased to 52.23 kg/m^{3}. The rhizosphere biomass on grazed pastures TOR had decreased to 77.99 kg/m^3. These low quantities of rhizosphere biomass are less than 20% of the potential rhizosphere biomass of 406.44 kg/m^3 recorded on silty ecological sites managed long-term with a twice-over rotation grazing strategy.

Rhizosphere organism biomass and activity are limited by access to simple carbon chains because the microflora trophic levels lack chlorophyll and have low carbon (energy) content. Partial defoliation of grass plants at vegetative phenological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbon compounds to be released through the plant roots into the rhizosphere. With the increase in availability of carbon compounds in the rhizosphere, activity of the microorganisms increases. The increase in rhizosphere organism activity causes an increase in rhizosphere volume and biomass. Without partial defoliation by grazing at specific grass growth stages, only small quantities of plant material leak from the grass roots into the rhizosphere; this low amount of carbon compounds is barely enough to sustain a small rhizosphere biomass at less than 20% of potential biomass (Manske 1999, 2011).

During the first two years of the study, the rhizosphere weights on the grazed pastures were numerically greater than the rhizosphere weights on the ungrazed control pasture, but were not significantly different. However, the rhizosphere weights on the grazed pastures became significantly greater than those on the ungrazed pasture during years 3 to 6 (table 10 and figure 1).

The rhizosphere weights on the ungrazed control pasture NG changed little during years 1 to 5. The changes in rhizosphere weight did appear to be responses to changes in growing season precipitation. The rhizosphere weights on the ungrazed pasture were not significantly different during years 1 to 3, when the mean growing season precipitation was 10.54 inches (71.26% of LTM). The rhizosphere weights during years 4 and 5 increased slightly when the mean growing season precipitation increased slightly to 12.53 inches (84.72% of LTM). The rhizosphere weights were not significantly different from each other during years 4 and 5 but were significantly greater than the rhizosphere weights during years 1 to 3. The rhizosphere weights increased greatly when the growing season precipitation increased greatly to 17.15 inches (115.96% of LTM) during year 6. The rhizosphere weights on ungrazed pasture NG were significantly greater during year 6 than those during years 1 to 5 (table 10 and figure 1). Changes in rhizosphere weights on the ungrazed pasture appeared to be related to changes in growing season precipitation, or more specifically to changes in the availability of hydrogen, which in turn effected the quantity of atmospheric carbon fixed during photosynthesis increasing the quantity of carbohydrates. With greater quantities of plant carbohydrates, the quantity of simple carbon compounds that leaked from grass roots into the rhizosphere increased proportionally, increasing the rhizosphere biomass. During this study, the rhizosphere biomass on the ungrazed pasture changed from 12.9% to 32.1% of the potential rhizosphere biomass on long-term twice-over rotation management strategies.

The rhizosphere weights on the grazed pastures TOR did not change significantly during years 1 and 2, and the rhizosphere weights on the grazed pastures were not significantly different than those on the ungrazed pasture during the first 2 years. The rhizosphere weights increased 33% between the second and third years on the grazed pastures and continued to increase weight at a mean rate of 30.5 kg/m^3 per year from the second year to the sixth year which was 131.5% greater than the change in rhizosphere weights on the ungrazed control pasture. The rhizosphere weights on the grazed pastures were significantly greater than those on the ungrazed control pasture each year from year three to year six (table 10 and figure 1). The rhizosphere biomass increases during years three to six on the grazed pastures appeared to be related to increases in carbon exudates that resulted from partial defoliation by grazing of grass lead tillers during vegetative growth stages. During this study, the rhizosphere biomass on the grazed pastures changed from 19.2% to 52.7% of the potential rhizosphere biomass on long-term twice-over rotation management strategies.

Six years of twice-over rotation grazing management increased the rhizosphere biomass 175% and improved the plant community composition of native grasses 43%, however, neither the rhizosphere or the plant community had been fully restored and require continuation of the grazing treatment.

Discussion

Traditionally, rangeland ecosystems have been managed from the perspective of the “use” of the grassland. Livestock grazing along with watershed, wildlife, and recreation were considered to be the major uses. Management of rangelands from the perspective of a single use or for multiple uses narrowly considers only a few ecosystem components directly related with these primary uses or products removed. Management for a use does not consider rangelands as complex ecosystems and neglects to address the needs of all other ecosystem components. Management of rangelands for a use results in degradation of the ecosystems.

Rangelands are complex ecosystems consisting of numerous interactive biotic (living) and abiotic (nonliving) components. The biotic components are the plants, soil organisms, and large grazing graminivores that have biological and physiological requirements. The abiotic components require the presence of sunlight and include the essential major elements of carbon, hydrogen, nitrogen, and oxygen that have transformable characteristics between organic and inorganic forms through biogeochemical processes. Rangeland ecosystems are functioning units of coacting biotic organisms interacting with the abiotic components and the environment. The complex of mechanisms and processes connected with these extensive interactions have been collectively identified as defoliation resistance mechanisms and biogeochemical processes. If any of the numerous processes are not functioning at potential level, the ecosystem does not produce at potential levels.

Management of rangeland ecosystems needs to meet the biological and physiological requirements of the biotic components and activate the biogeochemical processes that cycle the abiotic components. Mixed grass prairie communities require biologically effective partial defoliation by annually managed grazing animals in order to persist as healthy and productive ecosystems. Thus, providing the means to accomplish the uses of watershed, wildlife habitat, recreation, and livestock forage at the same time on fully functional rangeland ecosystems.

Implementation of the biologically effective twice-over rotation grazing management strategy activates the defoliation resistance mechanisms meeting the biological and physiological requirements of the biotic components and activates the biogeochemical processes that cycle the abiotic components (Manske 2011). The three main defoliation resistance mechanisms are : compensatory internal physiological processes, internal vegetative reproduction of secondary tillers from axillary buds, and external symbiotic rhizosphere organism activity (McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995; Manske 2009, 2011).

The defoliation resistance mechanisms developed early during the coevolution of grass plants and grazing graminivores (McNaughton 1979, 1983; Coleman et al. 1983; Briske 1991; Briske and Richards 1995; Manske 1999, 2011) and are a complex assemblage of biogeochemical and physiological processes that involve intricate interactions among rhizosphere microorganisms, grass plants, and large grazing graminivores. Activation of these mechanisms provides important biological and physiological processes permitting native grasses to produce greater herbage biomass and to increase basal cover; these mechanisms also enable grass plants to replace lost leaf material, to restore disrupted physiological processes, and to vegetatively reproduce secondary tillers from axillary buds after partial defoliation by grazing. The defoliation resistance mechanisms function at variable levels of activation depending on the quantity of available mineral nitrogen in the ecosystem soil and on the quantity of available recently fixed carbon (Richards and Caldwell 1985). When mineral nitrogen is available at 100 lbs/ac or greater, the defoliation resistance mechanisms function at full activation. When mineral nitrogen is available at less than 100 lbs/ac, the defoliation resistance mechanisms function at levels less than full activation (Manske 2009). In addition, the water (precipitation) use efficiency processes decrease in grass plants growing in ecosystems with less than 100 lbs/ac available mineral nitrogen causing herbage biomass production to be reduced by 49.6% (Wight and Black 1972, 1979).

The quantity of available mineral nitrogen in grassland ecosystem soils is dependant on the rate of mineralization of soil organic nitrogen by rhizosphere organisms. The larger the rhizosphere volume and microorganism biomass, the greater the quantity of soil mineral nitrogen converted. Rhizosphere volume and microorganism biomass are limited by access to simple carbohydrates (Curl and Truelove 1986). Healthy grass plants capture and fix carbon during photosynthesis and produce carbohydrates in quantities greater than the amount needed for tiller growth and development (Coyne et al. 1995). Partial defoliation of grass lead tillers at vegetative physiological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbohydrates to be released from the grass tillers through the roots into the rhizosphere (Hamilton and Frank 2001). With the increase in availability of carbon compounds in the rhizosphere, the biomass and activity of the microorganisms increases (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). The increase in rhizosphere organism biomass and activity results in greater rates of mineralization of soil organic nitrogen converting greater quantities of available mineral nitrogen (Coleman et al. 1983, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005). Mineral nitrogen available in quantities of 100 lbs/ac or greater allows partially defoliated grass tillers full activation of the defoliation resistance mechanisms (Manske 2009). Full activation of the compensatory internal physiological processes within grass plants accelerates growth rates of replacement roots, leaves, and shoots, increases photosynthetic capacity of remaining mature leaves, increases allocation of carbon and nitrogen, improves water (precipitation) use efficiency, and increases restoration of biological and physiological processes enabling rapid and complete recovery of partially defoliated grass tillers. Full activation of the asexual internal processes of vegetative reproduction increases secondary tiller development from axillary buds and increases initiated tiller density during the grazing season. Full activation of the external symbiotic rhizosphere organism activity increases mineralization of inorganic nitrogen, increases ecosystem biogeochemical cycling of essential elements, and improves belowground resource uptake competitiveness (Wight and Black 1972, 1979; McNaughton 1979, 1983; Coleman et al. 1983; Ingham et al. 1985; Mueller and Richards 1986; Richards et al. 1988; Briske 1991; Murphy and Briske 1992; Briske and Richards 1994, 1995; Manske 1999, 2011; Kochy and Wilson 2000).

Restoration of degraded mixed grass prairie ecosystems depends on the successfulness of recovery of the biogeochemical processes and revival of the indispensable component resources. The rhizosphere organism biomass must be improved initially to increase mineralization of nitrogen and other essential elements. Rhizosphere organisms increase when greater quantities of short carbon chain energy are exudated by partial defoliation by grazing. Two growing seasons are required before substantial increases in rhizosphere biomass occur. The rhizosphere biomass continues to increase as the quantity of short carbon chain energy exudated from native grasses increases.

Removal of substantial quantities of the overstory vegetation comprised of domesticated grass live and standing dead herbage biomass increases sunlight intensities reaching the understory native grass leaves sufficiently to enhance the photosynthetic rates and to increase the quantity of available fixed carbon. Reduction of adequate quantities of overstory vegetation requires grazing graminivores at relatively high stocking rates, around 85% to 100% of the assessed level. Stocking rates greater than 100% of assessed level can remove great quantities of overstory vegetation in a short time period. However, because native grass plants cannot fill the plant community open spaces rapidly, exposure of sunlight to large proportions of bare ground causes negative effects that initiate extreme increases in weedy forbs that remain problems for several years. Stocking rates less than 85% of assessed level remove insufficient quantities of overstory vegetation to effectively reduce the shading problem. Native grasses in the understory receiving insufficient sunlight continue to decline. Stocking rates between 85% and 100% of the assessed level remove enough overstory vegetation to permit an increased intensity of sunlight to reach the leaves of native grasses that increases the photosynthetic rates and fixes carbon at greater quantities sufficient for increased grass growth to progress at reasonable restoration rates.

Dead plant material does not decompose through microbial activity unless it makes contact with soil. Livestock do not preferentially consume old dead litter. However, the presence of the livestock caused greater proportions of the thick mulch to make soil contact and reduce the litter mulch biomass by greater than 70% of the litter biomass on areas without livestock.

Restoration of mixed grass prairie ecosystems degraded by traditional management concepts requires implementation of a biologically effective grazing management strategy that activates the ecosystem biogeochemical processes and the defoliation resistance mechanisms. The activation trigger for these processes and mechanisms is partial defoliation by large grazing graminivores that removes 25% to 33% of the aboveground leaf biomass from grass lead tillers at vegetative growth stages between the 3.5 new leaf stage and the flower (anthesis) stage (Manske 1999, 2011). In addition, reduction of the shading problem and of the thick mulch problem will assist the restoration process. Following recovery of some of the biogeochemical processes, the previously deficient quantities of available mineral nitrogen, essential elements, fixed carbon, and soil water start increasing upwards towards functional quantities. With the increase of component resources, native grass plants are able to synthesize increasing quantities of carbohydrates, proteins, and nucleic acids. Activation of the defoliation resistance mechanisms provides important biological and physiological processes permitting native grasses to use the vital organic compounds in increasing quantities for the production of herbage biomass and basal cover. Within a few years, the composition of native grasses increases in the plant community and becomes the dominant vegetation. The native grasses improve in competitiveness for the belowground resources of soil water, mineral nitrogen, and other essential elements which eventually reduces the remaining introduced domesticated grasses to minor composition in the plant community. The length of time required to reach recovery is related exponentially to the severity of degradation. The belowground ecosystem processes and mechanisms must be restored before the aboveground plant community can be restored.

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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. Mean herbage biomass (lbs/ac) for nongrazed silty native rangeland sites dominated by kentucky bluegrass.

Pasture NG	Pregrazing	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	1684.81	1833.85	1791.31	1320.16	1779.62	1468.69	2333.98
Cool Season	35.68	73.30	110.22	97.30	248.74	180.95	57.49
Warm Season	0.71	59.02	126.59	45.16	56.17	102.76	153.73
Native Grass	36.39	132.32	236.81	142.46	304.91	283.71	211.22
Sedges	7.14	25.91	22.27	20.29	49.44	30.48	11.82
Forbs	42.10	128.75	75.97	27.02	116.81	238.65	185.43
Total Live	1770.44	2120.83	2126.36	1509.93	2250.78	2021.53	2742.47
Standing Dead	1824.68	1381.12	708.48	928.70	499.32	432.54	1229.02
Litter	2785.89	2452.03	2131.29	2521.86	1946.39	1476.03	3178.78
Total Dead	4610.57	3833.15	2839.77	3450.56	2445.71	1908.57	4407.80
Total Biomass	6381.01	5953.98	4966.13	4960.49	4696.49	3930.10	7150.27

Table 3. Percent composition of herbage biomass for nongrazed silty native rangeland sites dominated by kentucky bluegrass.

Pasture NG	Pregrazing	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	95.16	86.47	84.24	87.43	79.07	72.65	85.11
Cool Season	2.02	3.46	5.18	6.44	11.05	8.95	2.10
Warm Season	0.04	2.78	5.95	2.99	2.50	5.08	5.61
Native Grass	2.06	6.24	11.13	9.43	13.55	14.03	7.71
Sedges	0.40	1.22	1.05	1.34	2.20	1.51	0.43
Forbs	2.38	6.07	3.57	1.79	5.19	11.81	6.76
Total Live	27.75	35.62	42.82	30.44	47.92	51.44	38.35
Standing Dead	28.60	23.20	14.27	18.72	10.63	11.01	17.19
Litter	43.66	41.18	42.92	50.84	41.44	37.56	44.46
Total Dead	72.25	64.38	57.18	69.56	52.08	48.56	61.65

Table 4. Basal cover (%) for nongrazed silty native rangeland sites dominated by kentucky bluegrass.

Pasture NG	Pregrazing	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	10.55	12.35	19.95	11.20	15.30	23.60	15.35
Cool Season	1.20	0.40	2.30	3.55	0.70	1.25	0.35
Warm Season	0.05	0.50	0.80	0.40	0.55	0.65	0.85
Native Grass	1.25	0.90	3.10	3.95	1.25	1.90	1.20
Sedges	2.85	2.00	2.20	1.90	2.35	1.75	1.05
Forbs	0.05	0.80	0.30	0.10	0.10	1.15	0.20
Total Live	14.80	16.05	25.55	17.15	19.00	28.40	17.85
Litter	85.20	83.95	74.45	82.85	81.00	71.60	82.15
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 5. Percentage composition (%) of basal cover for nongrazed silty native rangeland sites dominated by kentucky bluegrass.

Pasture NG	Pregrazing	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	71.28	76.95	78.08	65.31	80.53	83.10	85.99
Cool Season	8.11	2.49	9.00	20.70	3.68	4.40	1.96
Warm Season	0.34	3.12	3.13	2.33	2.89	2.29	4.76
Native Grass	8.45	5.61	12.13	23.03	6.57	6.69	6.72
Sedges	19.26	12.46	8.61	11.08	12.37	6.16	5.88
Forbs	0.34	4.98	1.17	0.58	0.53	4.05	1.12
Total Live	14.80	16.05	25.55	17.15	19.00	28.40	17.85
Litter	85.20	83.95	74.45	82.85	81.00	71.60	82.15

Table 6. Mean herbage biomass (lbs/ac) for grazed silty native rangeland sites dominated by kentucky bluegrass.

Pastures TOR	Pregrazing	Year1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	1066.48	954.70	1156.08	310.77	547.59	685.72	1261.24
Cool Season	43.53	177.90	300.19	188.95	395.69	307.77	518.18
Warm Season	10.00	28.19	42.21	22.79	48.58	38.99	48.89
Native Grass	53.53	206.09	342.40	211.74	444.27	346.76	567.07
Sedges	377.14	287.58	264.50	266.99	382.80	334.68	245.17
Forbs	147.72	122.28	77.06	35.17	94.50	357.87	100.11
Total Live	1644.85	1570.64	1840.03	824.67	1469.15	1725.02	2173.57
Standing Dead	1231.84	853.06	491.99	420.37	107.40	363.68	509.77
Litter	1661.26	1479.24	1030.31	1114.80	610.79	473.94	898.17
Total Dead	2875.10	2332.30	1522.30	1535.16	718.19	837.62	1407.93
Total Biomass	4520.05	3902.94	3362.33	2359.83	2187.34	2562.64	3581.51

Table 7. Percent composition of herbage biomass for grazed silty native rangeland sites dominated by kentucky bluegrass.

Pastures TOR	Pregrazing	Year1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	64.84	60.78	62.83	37.68	37.27	39.75	58.03
Cool Season	2.65	11.33	16.31	22.91	26.93	17.84	23.84
Warm Season	0.61	1.79	2.29	2.76	3.31	2.26	2.25
Native Grass	3.25	13.12	18.61	25.68	30.24	20.10	26.09
Sedges	22.93	18.31	14.37	32.38	26.06	19.40	11.28
Forbs	8.98	7.79	4.19	4.26	6.43	20.75	4.61
Total Live	36.39	40.24	54.72	34.95	67.17	67.31	60.69
Standing Dead	26.85	21.86	14.63	17.81	4.91	14.19	14.23
Litter	36.76	37.90	30.64	47.24	27.92	18.49	25.08
Total Dead	63.61	59.76	45.28	65.05	32.83	32.69	39.31

Table 8. Basal cover (%) for grazed silty native rangeland sites dominated by kentucky bluegrass.

Pastures TOR	Pregrazing	Year1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	3.45	4.80	5.35	4.08	6.20	6.88	6.88
Cool Season	1.85	1.85	6.83	4.08	4.98	6.08	3.93
Warm Season	0.43	0.70	1.83	2.73	2.63	1.58	2.53
Native Grass	2.28	2.55	8.66	6.81	7.61	7.66	6.46
Sedges	7.63	7.75	10.83	10.75	11.05	12.70	9.55
Forbs	0.58	0.45	0.43	0.20	0.45	3.05	0.50
Total Live	13.93	15.55	25.25	21.83	25.30	30.28	23.38
Litter	85.90	84.43	74.75	78.18	74.70	69.73	76.63
Total	99.83	99.98	100.00	100.00	100.00	100.00	100.00

Table 9. Percentage composition (%) of basal cover for grazed silty native rangeland sites dominated by kentucky bluegrass.

Pastures TOR	Pregrazing	Year1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	24.77	30.87	21.19	18.69	24.51	22.72	29.43
Cool Season	13.28	11.90	27.05	18.69	19.68	20.08	16.81
Warm Season	3.09	4.50	7.25	12.51	10.40	5.22	10.82
Native Grass	16.37	16.40	34.30	31.20	30.08	25.30	27.63
Sedges	54.77	49.84	42.89	49.24	43.68	41.94	40.85
Forbs	4.16	2.89	1.70	0.92	1.78	10.07	2.14
Total Live	13.93	15.55	25.25	21.83	25.30	30.28	23.38
Litter	85.90	84.43	74.75	78.18	74.70	69.73	76.63

Table 10. Rhizosphere weight (kg/m^3) for the control pasture and grazed pastures during six years of twice-over rotation management.

	Control Pasture kg/m^3	Grazed Pastures kg/m^3	% Difference
Pregrazing	52.23	77.99	49.32
Year 1	64.24x	83.28x	29.64
Year 2	77.82x	92.22x	18.50
Year 3	70.67y	122.61x	73.50
Year 4	82.88y	140.32x	69.31
Year 5	86.85y	183.00x	110.71
Year 6	130.56y	214.34x	64.17

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

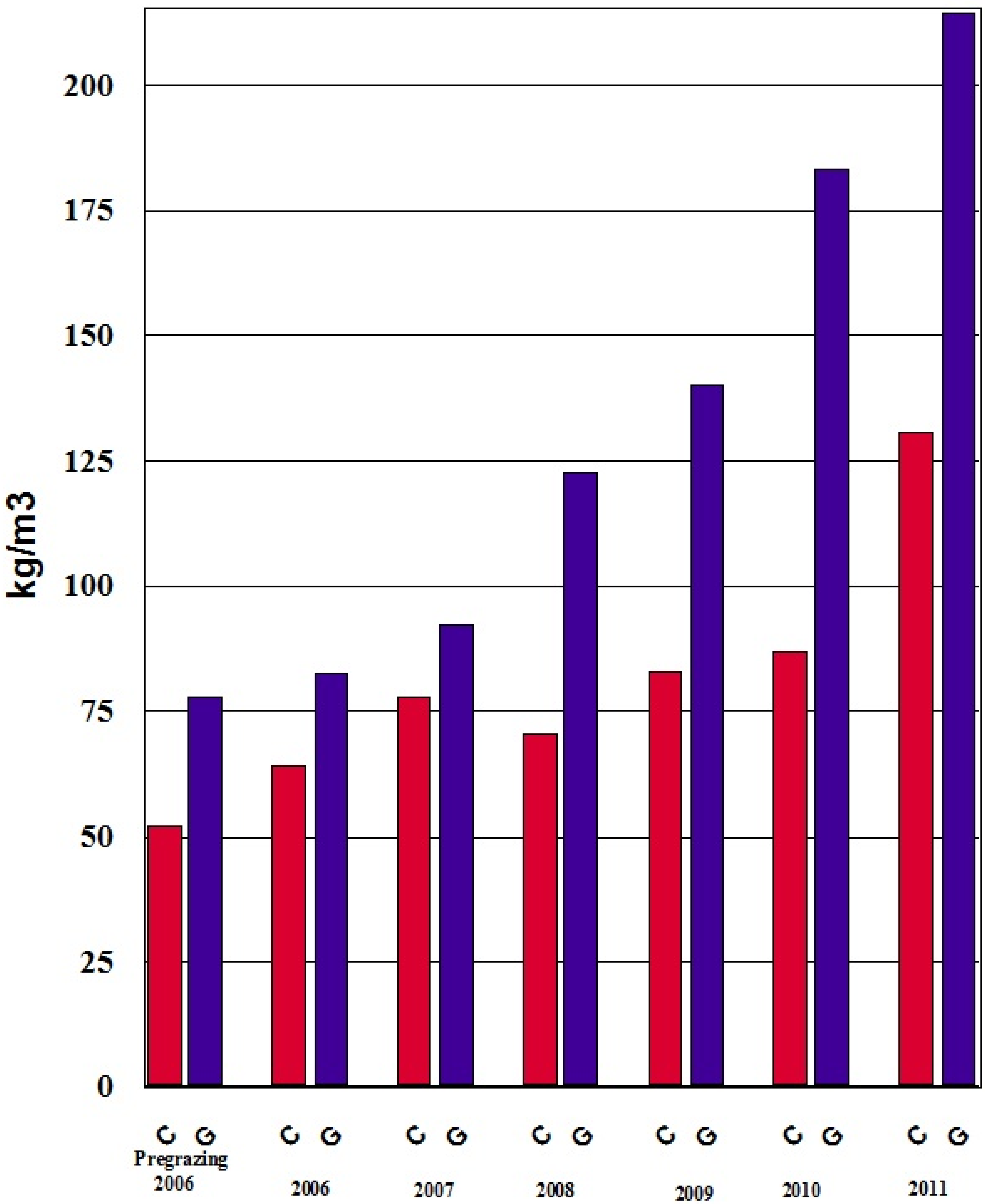

Figure 1. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

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