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Biologically Effective Management of Grazing

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Grazing is biologically beneficial for grass plants and for grassland ecosystems when grazing periods are coordinated with grass phenological growth stages (Whitman 1974).

The four primary physiological growth mechanisms within grass plants that perform the herbage replacement processes are activated with partial defoliation by grazing animals when 25% to 33% of leaf weight is removed from 60% to 80% of lead tillers during vegetative phenological growth stages between the three and a half new leaf stage and the flower stage when a threshold quantity of 100 lbs/ac (112 kg/ha) of mineral nitrogen is available (Manske 1999a). Unavailable soil organic nitrogen must be mineralized by soil microbes in order for nitrogen to be usable by grass plants. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of nitrogen yielding 100 lbs/ac. Grassland microbes are achlorophyllous and cannot fix their own carbon energy. Large quantities of surplus short chain carbon energy are produced by healthy vegetative lead tillers that can be exudated into the microbial rhizosphere when 25% to 33% of the leaf weight is removed with partial defoliation by grazing animals while lead tillers are between the three and a half new leaf stage and the flower stage (Manske 2018a). This treatment is applicable for crested wheatgrass and native grasses. Smooth bromegrass common varieties with southern parentage do not form symbiotic associations with rhizosphere microorganisms. On the other hand, the uncommon varieties with northern parentage readily form symbiotic associations with rhizosphere microorganisms (Manske 2017d). The four primary physiological growth mechanisms are not functional when less than 100 lbs/ac of mineral nitrogen is available and are not activated when zero % or greater than 33% of the leaf weight of lead tillers is removed during vegetative growth stages between the three and a half new leaf stage and the flower stage (Manske 2018a).

The three and a half new leaf stage is the phenological growth stage when grass lead tillers become physiologically capable of being grazed if only 25% to 33% of the tiller leaf weight is removed. Removal of 50% leaf weight is detrimental until after the flower stage (Manske 2010, 2014a, b, 2018c). The three and a half new leaf growth stage is the definitive signal showing when grasslands are ready for grazing to start. Perennial grass leaf growth stages of second year lead tillers is a simple, accurate, and dependable method to determine grazing readiness because development of the number of leaves is determined by the length of daylight resulting in a maximum year to year variance in grass species leaf growth stage of only 3 days with many common grasses having a variance of 1 day. Correct determination of grazing readiness by counting grass leaf stages requires a rudimentary understanding of how grasses grow.

The number of true seedlings is very low in a grassland and are negligible to the ecosystem. The grass in a grassland is almost always comprised of tillers produced vegetatively from axillary buds. Each tiller lives for two growing seasons. During the first growing season, grass tillers remain vegetative and can produce 6 to 8 leaves. During the second growing season, grass lead tillers produce a second set of 6 to 8 leaves plus development of flowers and seeds. At the end of each growing season, all tillers deactivate the chlorophyll and turn a tan color. Lead tillers that had produced flowers are terminal. Vegetative tillers that had produced only leaves remain alive through the winter by burning carbohydrates that were stored during the winter hardening period that occurs from mid August to around mid October. As a result of winter respiration by the carryover tillers, these carbohydrate reserves are nearly depleted and not adequate to support both root and new leaf growth the following growing season (Manske 2011).

Chlorophyll is reactivated during early spring in parts of old previous years leaves where the cells did not rupture. Usually, each carryover tiller has 2 or 3 previous years leaves that are half tan with ruptured cells and half green with complete intact cells. These green chlorophyll portions photosynthesize the material that will be used to produce the new current years leaves. New leaves of these second year lead tillers grow straight up from the apical meristem, located at the tiller base, through the old leaf sheaths until it reaches full size, then it tips to one side of the tiller. The next new leaf will tip to the other side of the tiller when it reaches full size and so on. When lead tillers are between the third new leaf stage and the three and a half new leaf stage, the apical meristem ceases production of leaf primordia and begins to produce flower primordia (Frank 1996, Frank et al, 1997). After three new full size leaves and a fourth new leaf, about half size and still growing straight up, have been produced, that lead tiller has sufficient leaf area to provide all of the photosynthetic assimilates required for additional new growth. The previously formed leaf buds will continue to grow and produce new full size leaves and later that growing season sexual reproductive floral structures will develop. The old carryover leaves are no longer required after the three and a half new leaf stage (Manske 2011).

These old carryover leaves will completely dry in a short time with portions of the leaves usually remaining attached towards the bottom of the lead tiller. Although the carryover leaves had activated chlorophyll and had photosynthesized assimilates during the current growing season, these leaves were produced during the previous growing season and should never be included in the count of new current years leaves. Including previous years leaves when counting the leaf growth stages of lead tillers causes a major problem by attributing that these tillers have reached the three and a half leaf stage at an earlier date than the biological date that they actually do reach grazing readiness, as would have been indicated by counting only the current years leaves to determine the three and a half new leaf stage. Starting grazing at an earlier leaf growth stage other than that at which the grass tillers are physiologically ready for grazing will undoubtedly cause noticeable degradation to that grassland and will subvert the intended purpose for using this technique.

Grass phenological stages of growth and development are triggered primarily by day length (Roberts 1939, Dahl 1995). In the northern hemisphere daylight hours increase during the growing season between mid April and 21 June and then decrease at the same rate of change each year. The leaf length and weight can be slightly modified by temperature and precipitation and will be variable from year to year (McMillan 1957, Dahl and Hyder 1977). The critical three and a half new leaf stage is not developed by all grass species at the same time or length of daylight. However, this leaf growth stage does occur during three seasonality time periods for similar grass types. The domesticated cool season grasses (crested wheatgrass and smooth bromegrass) are the first grass type to develop three and a half new leaves slightly before or near 1 May. The recommended grazing start date for domesticated cool season grass complementary spring pastures is 1 May (Manske 2017c, d). The native cool season grasses develop three and a half new leaves just before, on, or near 1 June. The native warm season grasses develop three and a half new leaves during mid June. The recommended grazing start date for native rangeland is 1 June (Manske 2018b). The wildryes (Altai and Russian) develop three and a half new leaves during early June. Wildryes are very different than other grasses biologically, they act as if they were types of perennial winter cereal with stimulation of the growth mechanisms during the fall, and they are negatively affected by traditional grass management practices. The recommended grazing start date for wildryes is mid October (Manske 2017a, b).

Crested wheatgrass starts early leaf greenup of vegetative carryover tillers in mid April. The crested wheatgrass lead tillers have three and a half new leaves around 22 April which is four to five weeks earlier than native cool season grasses. These early new leaves are highly nutritious with 16.3% crude protein, however, the available herbage weight is insufficient during April. Grazing can start 1 May. The nutritional quality of ungrazed lead tillers of crested wheatgrass changes with the tillers' phenological development. Early season growth stages are high in crude protein and water. Early vegetative leaf stages contain levels of crude protein above 15% during early to mid May. Early boot stage occurs in mid May. As seed stalks begin to develop, crude protein levels decrease. The first stalks with flowers occurs around 28 May. At the flower stage, lead tillers contain 13.5% crude protein. Most of the lead tillers reach the flower stage during a 10 to 14 day period. The late flowering lead tillers should flower by 10 June. During the flower stage period, crested wheatgrass herbage has the greatest weight of crude protein per acre available. After the flower stage, seed development occurs with crude protein levels remaining above 9.6% until late June. Native rangeland grasses contain greater crude protein levels at 15.5% to 12.0% during June. Crested wheatgrass seeds fill and reach maturity during the 5 to 8 weeks following flowering. As lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility (TDN) decrease. By early July, crude protein levels drop below 7.8% and below 6.2% in early August. Phosphorus levels drop below 0.18% in late July (Whitman et al. 1951, Manske 1999b, 2017c, 2018f).

The optimum period to graze domesticated crested wheatgrass complementary spring pastures is during the month of May.

Smooth bromegrass starts early leaf greenup of vegetative carryover tillers in mid April. Leaf development occurs slowly. The smooth bromegrass lead tillers have three and a half new leaves around early May, which is four or so weeks earlier than native cool season grasses. These early new leaves are highly nutritious with 17.6% crude protein. Grazing can start 1 May. The nutritional quality of ungrazed lead tillers of smooth bromegrass changes with the tillers' phenological development. Early season growth stages are high in crude protein above 18% during early to mid May. Smooth bromegrass is sensitive to early season heavy grazing. Early boot stage starts to occur in mid May developing slowly while crude protein levels decrease. Flower stalk emergence occurs in early June and first flowers appear around 13 June. At the flower stage, lead tillers contain 14.4% crude protein. Most of the lead tillers reach the flower stage by late June. During the flower stage period, smooth bromegrass herbage has the greatest weight of crude protein per acre available. After the flower stage, seed development occurs with crude protein levels remaining above 9.8% until late June. Native rangeland grasses contain greater crude protein levels at 15.5% to 12.0% during June. Smooth bromegrass seeds fill and reach maturity during the first week of July. As lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility (TDN) decrease. By early July, crude protein level drops below 9.5% and below 8.0% in early August. Phosphorus levels drop below 0.18% during early July (Whitman et al. 1951, Manske 1999b, 2017d). The optimum period to graze domesticated smooth bromegrass complementary spring pastures is during the month of May.

Native cool season grasses start early leaf greenup of vegetative carryover tillers in mid April and grow slowly until early May, reaching 59% of the leaf growth in height by mid May with crude protein levels above 16%. Most cool season grasses reach the three and a half new leaf stage around early June at 73% of the leaf growth in height, contain levels of crude protein above 15% during early to mid June, reach 94% of the leaf growth in height by late June, and 100% of the leaf growth height by late July. Cool season grasses start the flower stage period before 21 June. After the flower stage, crude protein levels begin to decrease below 15%. During the seed development stage, flower stalks reach 94% of the growth in height by late June and crude protein levels remain above 9.6% until mid July. The growth in height reaches 100% by late July when seeds are maturing and being shed. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility (TDN) decrease. During late July, crude protein levels drop below 8.0% and below 6.5% in late August (Whitman et al. 1951, Goetz 1963, Manske 2000, 2008b, 2018c, f). Partial defoliation managed by the twice-over rotation system activates secondary vegetative tillers. Crude protein levels of cool season secondary tillers increase above 9.6% during July and August to 13.2% in early September, decrease during September, and drop below 9.6% in early to mid October (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late July, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Native warm season grasses start early leaf greenup of vegetative carryover tillers in mid May, have crude protein levels above 15%, reach 44% of the leaf growth in height by early June, containing crude protein above 13% during early to mid June. Most warm season grasses reach the three and a half new leaf stage around mid June, reaching 85% of the leaf growth in height by late June and reach 100% of height by late July. Seed stalks begin to develop in mid June and reach the flower stage after 21 June with 12.2% crude protein. During the seed development stage, crude protein levels remain above 9.6% until late July when the flower stalks reach 91% of the growth in height. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility (TDN) decrease. During mid August, crude protein levels drop below 7.0%, seed stalks reach 100% of the growth in height by late August when the seeds are mature and being shed, and drop below 6.0% in crude protein by early September (Whitman et al. 1951, Goetz 1963, Manske 2000, 2008b, 2018c, f). Partial defoliation managed by the twice-over rotation system activates secondary vegetative tillers. Crude protein levels of warm season secondary tillers increase above 9.0% during August to 10.0% in early September, decreases during September, and drop below 9.6% in late September (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late August, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Crude protein levels of upland sedges do not follow the same relationship with phenological growth stages as in cool and warm season grasses. Crude protein levels in upland sedges remain high through the flower and seed mature stages. Upland sedges grow very early and produce seed heads in late April to early May and crude protein remains above 9.6% until mid July. Crude protein levels decrease with increases in senescence and drop below 7.8% in early August but do not fall below 6.2% for the remainder of the growing season (Whitman et al. 1951, Manske 2008b, 2018f). Phosphorus levels drop below 0.18% in mid May when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Wildryes, Altai and Russian, start early leaf greenup of vegetative carryover tillers in mid April. Leaf development occurs slowly. The lead tillers of wildryes develop three and a half new leaves during early June. Flower stalks develop during mid May to mid June, before the 21st, and are stiff, mostly leafless, and unpalatable to livestock. The leaves of lead tillers contain crude protein at levels above 12% during most of the growing season. However, lightly grazing wildryes prior to the flower stage does not activate vegetative tillers as in other grasses. Early season grazing actually decreases tiller basal cover. Fall grazing during mid October to mid November that removes less than 50% of the standing leaf biomass greatly increases vegetative secondary tiller and fall tiller development during the following summer and early fall. Removal of greater than 50% of the herbage biomass during the fall grazing periods greatly reduces active lead tiller growth followed by critical reductions in herbage biomass and nutritional quality during subsequent growing seasons eventually causing termination of a major portion of the living crown tillers that results in stand depletion within 20 to 25 years.

Leaving 50% of the herbage biomass in mid November is absolutely necessary for proper development of the vegetative and fall tillers during the following season. The basal leaves and flower stalks of the current lead tillers compose most of the standing herbage biomass during June. After the flower stage, the crude protein content of the basal leaves starts to decrease slowly. The vegetative tillers, that had been activated by the previous fall grazing period, begin visible growth shortly after the lead tiller stalks reach the flower stage. The herbage biomass during July and August consist of both the slowly aging lead tiller leaves and the rapidly growing vegetative tillers. The fall tillers develop after mid August producing substantial herbage biomass during September and October. By mid October, the fall tillers contain around 10% to 12% crude protein, the vegetative tillers contain around 8% to 10% crude protein, and the lead tillers contain around 6% to 8% crude protein. The ratio of the three tiller types affects the mean available crude protein level. Ungrazed wildrye plants produce very low quantities of vegetative and fall tillers showing low quantities of crude protein during fall. Annually grazed wildryes are the only perennial grass type that can provide adequate nutritional quality after mid October to meet a lactating cows requirements during a fall grazing period from mid October to mid November that leaves 50% of the herbage biomass at the end of the grazing period (Manske 2017a, b; 2018e, f).

The four primary physiological grass growth mechanisms are: compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake competitiveness, and water use efficiency (Manske 2018a, c).

The compensatory physiological mechanisms give grass plants the capability to replace lost leaf and shoot biomass following grazing by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen (McNaughton 1979, 1983; Briske 1991). Fully activated mechanisms can produce replacement foliage at 140% of the weight that was removed during grazing (Manske 2009).

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds and the subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young leaves. Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the quantity of auxin which then allows cytokinin, a growth hormone, to stimulate the meristematic tissue of multiple axillary buds to develop into vegetative secondary tillers (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995).

Nutrient resource uptake competitiveness determines the level of grass plant dominance within a grassland community. Removal of aboveground leaf material from grass plants affects root functions. Removal of 50% or more leaf material greatly reduces root growth, root respiration, and root nutrient and water absorption resulting in severe degradation of the functionality of grass plants (Crider 1955). Reduction of active root biomass causes diminishment of grass plant health and vigor (Whitman 1974) that result in a loss of resource uptake efficiency and a suppression of the competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water.

Reduction of grass plant nutrient uptake competitiveness allows successful establishment of undesirable grasses, weedy forbs, and shrub seedlings and rhizomes into grassland communities (Li and Wilson 1998, Kochy 1999, Kochy and Wilson 2000, Peltzer and Kochy 2001).

Water use efficiency in grass plants is not at a single constant rate. Precipitation (water) use efficiency of grass plants improves when soil mineral nitrogen is available at threshold quantities of 100 lbs/ac (112 kg/ha) and greater. The inhibitory deficiencies of mineral nitrogen on grasslands that have less than 100 lbs/ac of available soil mineral nitrogen cause the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystems that have greater than 100 lbs/ac of mineral nitrogen (Wight and Black 1972, 1979).

The vegetative reproduction by tillering and the compensatory physiological mechanisms function at remarkably high rates on grasslands that have greater than 100 lbs/ac of available mineral nitrogen and these mechanisms do not function or function at extremely low rates on grasslands that have mineral nitrogen deficiencies at less than 100 lbs/ac (Manske 2009, 2014c, 2018d).

Continuous functionality at high production rates of the four primary physiological grass growth mechanisms requires partial defoliation by grazing that removes 25% to 33% of leaf weight from 60% to 80% of the lead tillers between the three and a half new leaf stage and the flower stage annually with mineral nitrogen available at 100 lbs/ac or greater (Manske 1999a, 2014c, 2018a). This requirement is applicable to all perennial grasses except the wildryes. For the wildryes, the vegetative reproduction by tillering and the compensatory physiological mechanisms are activated by partial defoliation during a mid October to mid November annual grazing period (Manske 2017a, 2018f).

Rhizosphere microbes with a high biomass from 214 to 406 kg/m^3 (363 to 689 lbs/yd^3) can mineralize 111.3 to 176.3 kg/ha (99.4 to 157.4 lbs/ac) of mineral nitrogen (Manske 2018d). A large biomass of rhizosphere microorganisms can perform all of the grassland ecosystem biogeochemical processes that renew nutrient flow activities in the intact grassland soil. Biogeochemical processes transform stored essential elements from organic forms into plant-usable inorganic forms. Biogeochemical processes also capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen, with assistance from active live plants, and transform the captured major essential elements into storage as organic forms for later use. And the biogeochemical processes also decompose complex unusable organic material into compounds and then into reusable essential elements (Manske 2018a).

Management of grazing has traditionally been designed to provide forage for livestock with sensible stewardship for the aboveground portions of grass plants and with provisions for wildlife. Grassland ecosystems are much more complex than the traditional concept and consist of three principal interactive biotic components that have specific biological requirements.

The indispensable biotic components of a functional grassland ecosystem are grass vegetation, rhizosphere organisms, and domesticated cattle. Grazing livestock depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short carbon chain energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing livestock. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing livestock on which they depend.

Biologically Effective Management

The perennial forage grasses that grow in the Northern Mixed Grass Prairie region with similar phenological growth characteristics can be categorized into three seasonality time periods (grazing periods) in which the herbage production curves and the nutrient quality curves of the forage grasses match the biological and physiological requirements of each grazing cow with a calf. The spring seasonality period forage grasses support grazing during early to late May and include the introduced domesticated cool season grasses, such as crested wheatgrass and smooth bromegrass. The summer seasonality period forage grasses support grazing during early June to mid October and include the cool season and warm season native grasses. The fall seasonality period forage grasses support grazing during mid October to mid November and include the wildryes, such as Altai and Russian.

The forage grasses from the three seasonality time periods can be combined to form a biologically effective strategy that has spring and fall complementary pastures with summer native rangeland pastures designed to coordinate partial defoliation events with grass phenological growth stages, to meet the nutrient requirements of the grazing livestock, the biological requirements of the grass plants and the rhizosphere microorganisms, to enhance the ecosystem biogeochemical processes, and to activate the four primary internal grass plant physiological growth mechanisms in order for grassland ecosystems to function at the greatest achievable levels.

The Spring Seasonality Period

A domesticated cool season grass complementary spring pasture of crested wheatgrass or smooth bromegrass has been traditionally grazed from 1 to 31 May on one pasture. Productivity can be greatly increased by splitting that pasture in half with each half pasture grazed for two periods of 7 days for a total of 28 days called a two pasture switchback system. With this simplified version, the pasture switch can always be made during the same day each week i.e. on four May Monday mornings at 8:00 am. A more complicated version can add 4 grazing days by making the pasture switch on 8 day periods. This will add one weekday to each rotation and these days should probably be marked on a calendar.

Using the two pasture switchback system on crested wheatgrass with two 7 or 8 day grazing periods on each pasture activated functioning of the vegetative reproduction by tillering and the compensatory physiological mechanisms at much higher rates during May than the performing rates on a traditional single pasture strategy. On the two pasture switchback system herbage biomass was produced at 2183 lbs/ac, supporting a stocking rate at 1.30 ac/AUM, and calf weight gain at 66.6 lbs/ac. On the traditional single pasture strategy herbage biomass was produced at 1261 lbs/ac, supporting a stocking rate at 2.33 ac/AUM, and calf weight gain at 32.9 lbs/ac. The grass growth mechanisms functioning at higher rates on the two pasture switchback system increased herbage biomass production 73.1% greater, increased the stocking rate 79.2% greater, and increased calf weight gain 102.5% greater per acre than the productivity on the traditional strategy (Manske 2018f).

Livestock are moved to native rangeland pastures during early June. Native grasses have greater crude protein content during June than either crested wheatgrass or smooth bromegrass and activation of the important secondary vegetative tillers requires partial defoliation by grazing native grasses during 7 to 17 days on each pasture during the first grazing period of 45 days from 1 June to 15 July.

The Summer Seasonality Period

The twice-over rotation grazing management strategy uses three to six native grassland pastures. Each pasture is grazed for two periods per growing season. The number of grazing periods is determined by the number of sets of tillers: one set of lead tillers and one set of vegetative secondary tillers per growing season. The first grazing period is 45 days long, ideally, from 1 June to 15 July, with each pasture grazed for 7 to 17 days (never less or more). The number of days of the first grazing period on each pasture is the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture to the complete system. The forage is measured as animal unit months (AUM's). The average grazing season month is 30.5 days long (Manske 2012). The number of days grazed are not counted by calendar dates but by the number of 24-hr periods grazed from the date and time the livestock are turned out to pasture. The second grazing period is 90 days long, ideally from 15 July to 14 October, each pasture is grazed for twice the number of days as in the first period. The length of the total grazing period is best at 135 days; 45 days during the first period plus 90 days during the second period. There is some flexibility in the grazing period dates. The starting date has a variance of plus or minus 3 days with a range of start dates from 29 May to 4 June. This gives an extreme early option to start on 29 May with the first period to 12 July and with the second period to 11 October. The extreme late alternative option can start on 4 June with the first period to 18 July and with the second period to 17 October. There is also the option to add a total of 2 days to the total length of the grazing period. These 2 days can be used when a scheduled rotation date occurs on an inconvenient date by adding one day to each of two rotation dates. The limit of additional days is two per year resulting in a total length of 137 days. If inconvenient rotation dates occur during 3 or more times, an equal number of days greater than two must be subtracted from the grazing season, so total number of days grazed per year does not exceed 137 days. If the start date is later than 4 June, the scheduled rotation dates must remain as if the start date were on 4 June, in order to maintain the coordinated match of the partial defoliation events with the grass phenological growth stages. The total number of days grazed will be 135 days minus the number of days from 4 June to the actual start date. However, it is best to start on 1 June each year.

During the first period, partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers between the three and a half new leaf stage and the flower stage increases the rhizosphere microbe biomass and activity, enhances the ecosystem biogeochemical processes, and activates the internal grass plant growth mechanisms. Manipulation of these processes and mechanisms does not occur at any other time during a growing season. During the second grazing period, the lead tillers are maturing and declining in nutritional quality and defoliation by grazing is only moderately beneficial to grass development. Adequate forage nutritional quality during the second period depends on the activation of sufficient quantities of vegetative secondary tillers from axillary buds during the first period. Livestock are removed from intact grassland pastures in mid October, towards the end of the perennial grass growing season, in order to allow the carryover tillers to store the carbohydrates and nutrients which will maintain plant mechanisms over the winter. Most of the upright vegetative tillers on grassland ecosystems during the autumn will be carryover tillers which will resume growth as lead tillers during the next growing season. Almost all grass tillers live for two growing seasons, the first season as vegetative secondary tillers and the second season as lead tillers. Grazing carryover tillers after mid October causes the termination of a large proportion of the population, resulting in greatly reduced herbage biomass production in subsequent growing seasons. The pasture grazed first in the rotation sequence is the last pasture grazed during the previous year. The last pasture grazed has the greatest live herbage weight on 1 June of the following season (Manske 2018a).

Stocking rates are based on peak herbage biomass on seasonlong grazing practices. The starting stocking rate on the "new" twice-over grazing practice is usually 80% to 100% of the seasonlong stocking rate. It usually requires three grazing seasons with the twice-over strategy stocked at 100% to increase the rhizosphere microbe biomass to be great enough to mineralize 100 lbs/ac of mineral nitrogen (nitrate NO_3 and ammonium NH_4). After the increased rhizosphere microbe biomass can mineralize 100 lbs/ac of mineral nitrogen, the stocking rate can be increased at 10% per year until the system is stocked at 140% of the seasonlong stocking rate. This has been the maximum biological potential reached on North American grasslands from the twice-over rotation strategy.

Once a rotation date scheduled has been determined, do not change that schedule greater than one day for any worldly reason. If you do not like your neighbors bull, build a fence that the bull cannot jump. If you have water sources that sometimes go dry, put in a water tank system on a pipeline. Fix the problems that develop with solutions that do not change the rotation schedule.

Using a three pasture twice-over rotation system activated functioning of the four primary grass physiological growth mechanisms at much higher rates during the summer grazing period of 1 June to 14 October than the performing rates on a traditional seasonlong native rangeland pasture strategy. On the twice-over rotation system, the higher functioning rates of the grass growth mechanisms increased growing season native grass herbage biomass 31.2% greater, cool season lead tiller biomass was 25.5% greater during July and secondary vegetative tiller biomass was 50.7% greater during September, warm season lead tiller biomass was 16.1% greater during August and secondary vegetative tiller biomass was 29.9% greater during September and October, stocking rate was 14.2% greater, calf weight gain per acre was 23.0% greater, and cow weight gain per acre was 46.9% greater than the productivity on the traditional seasonlong strategy (Manske 2018f).

The Fall Seasonality Period

A domesticated wildrye complementary fall pasture of Russian or Altai wildrye has not been a widely accepted practice. Wildrye are biologically different than other grasses and plant density decreases when managed with standard practices typically used with native grasses. Vegetative secondary tiller and fall tiller development of wildryes are activated by partial defoliation grazing during the fall from mid October to mid November and leaving 50% of the standing herbage biomass. Removing greater than 50% of the herbage results in harsh reductions in productivity. However, by leaving 50% residual vegetation annually, the potential herbage production can be greater than 3000 lbs/ac. Annually grazed wildryes are the only perennial grass type that provides adequate nutritional quality to meet a lactating cows requirements during fall grazing from mid October to mid November.

Using an Altai wildrye pasture during mid October to mid November and leaving 50% residual herbage biomass provided 3141 lbs/ac herbage with a mean content of 10.2% crude protein. A reserved late season native rangeland pasture provided 891 lbs/ac herbage with a mean content of 4.8% crude protein. On the Altai wildrye pasture, the vegetative reproduction by tillering and the compensatory physiological mechanisms were activated during the fall grazing period producing 252.5% greater herbage biomass, supporting a stocking rate at 191.5% greater, with calf weight gains per acre at 747.5% greater, and cow weight gains per acre at 349.8% greater than the productivity on the reserved native rangeland pasture (Manske 2018f).

Providing forage for livestock is not the only purpose for grazing grasslands. Grass plants have biological requirements and have four primary physiological growth mechanisms that must be activated by partial defoliation by grazing. Rhizosphere microorganisms are needed in large quantities to perform all of the ecosystem biogeochemical processes, but are unable to fix carbon energy and require exudated short chain carbon energy that can be provided by partial defoliation by grazing. The three indispensable biotic components of grasslands; grass vegetation, rhizosphere organisms, and domesticated livestock; must have their biological requirements provided with partial defoliation by grazing in order for grassland ecosystems to function at achievable levels.

Biologically effective management of grazing has been developed for modern high-performance beef livestock and is able to provide the biological and physiological requirements to the forage grass plants, soil microorganisms, and grazing livestock, able to activate and maintain the grass plant growth mechanisms and the ecosystem biogeochemical processes, able to revitalize soil structure, aggregation, and functionality, able to increase forage quantity and nutritional quality, and able to improve livestock growth and performance along with the capture of greater wealth per acre from renewable grassland natural resources.

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Grass Vegetation:
An Indispensable Biotic Component of the Northern Mixed Grass Prairie

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

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component part and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains. The introduction to this study can be found in report DREC 16-1093 (Manske 2016).

Grass vegetation, rhizosphere organisms, and domesticated graminivores are indispensable biotic components of a functional rangeland ecosystem. Grazing graminivores depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short carbon chain energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing graminivores. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing graminivores on which they depend.

The three indispensable biotic components of rangeland ecosystems: Grass Vegetation, Rhizosphere Organisms, and Domesticated Graminivores will each be quantitatively described in separate companion reports. This report will provide quantitative knowledge of grass vegetation as an indispensable biotic component of grassland ecosystems.

Indispensable Grass Vegetation

Grass vegetation on a fully functional grassland ecosystem can be perpetually sustainable with biologically effective management that activates the ecosystem biogeochemical processes and the grass plant physiological mechanisms to function at potential levels. When these processes and mechanisms function above threshold levels, capture and replenishment of input essential elements occurs at greater quantities than the amount of output essential elements maintaining the ecosystem.

Grass Tiller Growth and Development

Grass plants use the major and minor essential elements in the inorganic form to synthesize vital organic compounds of carbohydrates, proteins, and nucleic acids for growth. Grass tillers consist of shoots and roots (figure 1). The shoot is the stem and leaves comprised of repeated phytomers (Beard 1973, Dahl 1995). A phytomer consists of a leaf, with a blade and a sheath separated by a collar, a node, an internode, and an axillary bud (Hyder 1974, Dahl and Hyder 1977). Each tiller shoot generally produces 6 to 8 phytomers per growing season (Langer 1972, Dahl 1995). Longevity of grass tillers extends two growing seasons (Langer 1956, Butler and Briske 1988, Manske 2009, 2014a). Phytomers develop from leaf primordia that form on alternating sides of the apical meristem (Evans and Grover 1940, Langer 1972, Beard 1973, Dahl 1995). Almost all of the phytomer cells are produced in the apical meristem while the leaf primordia is a minute bud (Langer 1972). Growth of the leaf results through cell enlargement and elongation (Esau 1960, Dahl 1995). Once a leaf blade is fully expanded, it has its greatest dry weight and no further growth of that blade is possible (Dahl 1995). Grass tillers remain vegetative during the first growing season, overwinter, and resume growth during the second subsequent growing season (Briske and Richards 1995). Production of new leaf primordia continues until the status of the apical meristem changes from vegetative to reproductive (Dahl 1995, Briske and Richards 1995). When the second year lead tiller is between the third new leaf stage and the three and a half new leaf stage, the apical meristem ceases to produce leaf primordia and begins to produce flower primordia (Frank 1996, Frank et al. 1997). The flower bud primordia develop into the inflorescence with the apical dome becoming the terminal spikelet (Langer 1972). Previously formed leaf buds continue to grow and develop (Esau 1960, Langer 1972) until the flower stalk elongates (Dahl 1995). The life cycle of a grass tiller terminates during the end of the second growing season because production of additional leaves is no longer possible (Briske and Richards 1995).

Grass Plant Mechanisms

The key factor in meeting grass plant biological requirements is proper timing of partial defoliation. The effects of defoliation are not simply the removal of herbage from grass plants (Langer 1963, 1972): foliage removal disrupts plant growth and photosynthesis, and defoliation also changes physiological mechanisms in all parts of the plant; alters the plant community microclimate by changing light transmission, moisture relations, and temperature (Briske and Richards 1994, 1995); and changes the soil environment, thereby affecting soil organism activity and ecosystem biogeochemical processes (Manske 2000a, 2011a). Internal plant mechanisms help grass tillers withstand and recover from partial defoliation by grazing. The primary mechanisms are: compensatory physiological mechanisms (McNaughton 1979, 1983; Briske 1991); vegetative reproduction by tillering (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995); nutrient resource uptake (Crider 1955, Li and Wilson 1998, Kochy and Wilson 2000, Peltzer and Kochy 2001); and water use efficiency (Wight and Black 1972, 1979).

Compensatory Physiological Mechanisms

The compensatory physiological mechanisms give grass plants the capability to replace lost leaf and shoot biomass following grazing by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen. Fully activated mechanisms can produce replacement foliage at 140% of the weight that was removed during grazing (Manske 2000b, 2010a, b, 2014a, b). The growth rates of replacement leaves and shoots increase after partial defoliation by grazing. The enhanced activity of meristematic tissue produces larger leaves with greater mass (Langer 1972, Briske and Richards 1995). Developing leaf primordia not fully expanded at time of defoliation have increased growth rates and tend to grow larger than leaves on undefoliated tillers (Langer 1972). Partial defoliated tillers increase photosynthetic rates of remaining mature leaves and rejuvenated portions of older leaves not completely senescent (Atkinson 1986, Briske and Richards 1995). Changes in cytokinin levels and other signals produced as a result of the increase in the root-shoot ratio rejuvenate the photosynthetic apparatus, inhibit or reduce the rate of senescence, and increase the lifespan and leaf mass of remaining mature leaves (Briske and Richards 1995). Activation of the compensatory physiological mechanisms after partial defoliation of grass tillers by grazing requires alternative sources of abundant carbon and nitrogen (Coyne et al. 1995). Carbon fixed during current photosynthesis in remaining mature leaf and shoot tissue and rejuvenated portions of older leaves is preferentially allocated to areas of active meristematic tissue (Ryle and Powell 1975, Richards and Caldwell 1985, Briske and Richards 1995, Coyne et al. 1995). The quantity of leaf area required to fix adequate quantities of carbon is 67% to 75% of the predefoliated leaf area (Manske 1999, 2011a, 2014c). Very little, if any, of the carbon and nitrogen stored in the root system is remobilized to support compensatory growth (Briske and Richards 1995). The mobilizable nitrogen pools in the shoot tissue are reduced following partial defoliation. This loss in nitrogen from the shoot increases preferential use of the quantities of mineral nitrogen available in the media around the roots (Millard et al. 1990, Ourry et al. 1990). This available soil mineral nitrogen has been converted from soil organic nitrogen by active rhizosphere organisms, absorbed through the roots, and moved to areas of active meristematic tissue.

Vegetative Reproduction by Tillering

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds by the process of tillering (Dahl 1995) (figure 2). Meristematic activity in axillary buds and the subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young developing leaves (Briske and Richards 1995). Tiller growth from axillary buds is inhibited indirectly by auxin interference with the metabolic function of cytokinin, a growth hormone (Briske and Richards 1995). Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the production of the blockage hormone, auxin (Briske and Richards 1994). This abrupt reduction of plant auxin in the lead tiller allows for cytokinin synthesis or utilization in multiple axillary buds, stimulating the development of vegetative secondary tillers (Murphy and Briske 1992, Briske and Richards 1994). If no defoliation occurs before the flower (anthesis) stage, the lead tiller continues to hormonally inhibit secondary tiller development from axillary buds. Production of the inhibitory hormone, auxin, declines gradationally as the lead tiller reaches the flower stage. The natural reduction of auxin in the lead tiller usually permits only one secondary tiller to develop. This developing secondary tiller produces auxin that hormonally suppress development of additional axillary buds (Briske and Richards 1995). Vegetative tiller growth is the dominant form of reproduction in semiarid and mesic grasslands (Belsky 1992, Chapman and Peat 1992, Briske and Richards 1995, Chapman 1996, Manske 1999) not sexual reproduction and the development of seedlings. Recruitment of new grass plants developed from seedlings is negligible in healthy grassland ecosystems. The frequency of true seedlings is extremely low in functioning grasslands, and establishment of seedlings occurs only during years with favorable moisture and temperature conditions (Wilson and Briske 1979, Briske and Richards 1995), in areas of reduced competition from vegetative tillers, and when resources are readily available to the growing seedling.

Nutrient Resource Uptake

Grass plant dominance within a grassland community is related to the plants competitiveness at nutrient and water resource uptake. Crider (1955) found that grass tillers with 50% or more of the aboveground leaf material removed reduce root growth, root respiration, and root nutrient absorption resulting in reduced functionality of these grass plants. Reduction of active root biomass caused diminishment of grass plant health and vigor (Whitman 1974) that 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 contributed to the reduction of rhizosphere biomass and the decline of ecosystem biogeochemical processes (Coleman et al. 1983, Klein et al. 1988). The nutrient resource uptake competitiveness of healthy grasses is able to suppress the expansion of shrubs and prevent successful establishment of grass, forb, and shrub seedlings into grasslands (Peltzer and Kochy 2001). The grass growth form has competitive advantages of nutrient uptake over the shrub growth form (Kochy and Wilson 2000). Grass aboveground biomass is primarily productive photosynthetic leaves resulting in a high resource uptake efficiency. Grasses are good competitors for belowground nutrient resources and superior competitors for mineral nitrogen because of a high root: shoot ratio and no woody stems to maintain. Shrubs have a great reduction in resource uptake efficiency because a large portion of the photosynthates produced in the leaves must be used to build and maintain their unproductive woody stems. However, the taller woody stems make shrubs superior competitor for aboveground sunlight resources (Kochy and Wilson 2000). Competition for belowground nutrient resources from healthy grasses reduce the growth rates of shrub rhizomes and cause high mortality rates of young suckers (Li and Wilson 1998). Shrubs can compete for some of the belowground resources only after the grass plants have been degraded by ineffective management. Following the reduction in grass plant resource uptake competitiveness, the belowground resources no longer consumed by the smaller, less vigorous degraded grasses, are taken up by the shrub plants resulting in proportional increases of biomass production (Kochy and Wilson 2000). With greater nutrient resources, shrub rhizome suckers are able to establish a faster growth rate and a higher survival rate (Li and Wilson 1998). The resulting greater shrub stem density increases the competition for the aboveground resources of light causing strong suppression of the grasses (Kochy and Wilson 2000). Traditionally, the observation of increasing woody shrubs and trees into degraded grasslands would have been explained as a result of fire suppression (Humphrey 1962, Stoddart, Smith, and Box 1975, Wright and Bailey 1982).

Water Use Efficiency

Grasslands of the Northern Plains managed with traditional practices are notorious for their inhibitory deficiency in available soil mineral nitrogen (Goetz et al. 1978) which has been determined to cause the observed low herbage production. Deficiencies in mineral nitrogen limit herbage production more often than water in temperate grasslands (Tilman 1990). The total herbage biomass production on grassland ecosystems has been shown to increase with increases in the quantity of available soil mineral nitrogen (Rogler and Lorenz 1957; Whitman 1957, 1963, 1976; Smika et al. 1965; Goetz 1969, 1975; Power and Alessi 1971; Lorenz and Rogler 1972; Taylor 1976; Wight and Black 1979). Greater quantities of available soil mineral nitrogen has been shown to also cause the soil water use efficiency to improve in grassland plants (Smika et al. 1965, Wight and Black 1972, Whitman 1976, 1978). Using a proxy method, Wight and Black (1972) found that precipitation (water) use efficiency of grass plants improved when soil mineral nitrogen was available at threshold quantities of 100 lbs/ac and greater. The inhibitory deficiencies of mineral nitrogen on grasslands that had less than 100 lbs/ac of available soil mineral nitrogen caused the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystems that had greater than 100 lbs/ac of mineral nitrogen and did not have mineral nitrogen deficiencies (Wight and Black 1979). The efficiency of water use in grass plants function at low levels when mineral nitrogen is deficient and function at high levels when mineral nitrogen is available at threshold quantities of 100 lbs/ac or greater. The level of water use efficiency determines the level of herbage biomass productivity on grasslands.

Manske (2010a, b) found that the threshold quantity of 100 lbs/ac of available mineral nitrogen was also critical for functionality of the vegetative reproduction and the compensatory physiological mechanisms. Both these mechanisms function at high potential levels on grasslands that have 100 lbs/ac or greater available soil mineral nitrogen and do not function or function at extremely low levels on grasslands that have mineral nitrogen deficiencies (Manske 2009, 2010a, b, c, 2011b).

Grass Nutrient Quality Related to Phenological Stages

The available nutritional quality of pregrazed lead tillers of native cool and warm season grasses is closely related to the phenological stages of growth and development, which are triggered primarily by the length of daylight (Roberts 1939, Dahl 1995). The length of daylight increases during the growing season between mid April and 21 June and then decreases. All native cool and warm season grasses have adequate levels of energy throughout the growing season.

Native cool season grasses start early leaf greenup of vegetative carryover tillers in mid April and grow slowly until early May, reaching 59% of the leaf growth in height by mid May with crude protein levels above 16%. Most cool season grasses reach the 3.5 new leaf stage around early June at 73% of the leaf growth in height, contain levels of crude protein above 15% during early to mid June, reach 94% of the leaf growth in height by late June, and 100% of the leaf growth height by late July. Most cool season grasses reach the flower stage before 21 June. After the flower stage, crude protein levels begin to decrease below 15%. During the seed development stage, flower stalks reach 94% of the growth in height by late June and crude protein levels remain above 9.6% until mid July. The growth in height reaches 100% by late July when seeds are maturing and being shed. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During late July, crude protein levels drop below 8.0% and below 6.5% in late August (Whitman et al. 1951, Goetz 1963, Manske 2000c, 2008b). Crude protein levels of cool season secondary tillers increase above 9.6% during July and August to 13.2% in early September, decrease during September, and drop below 9.6% in early to mid October (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late July, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

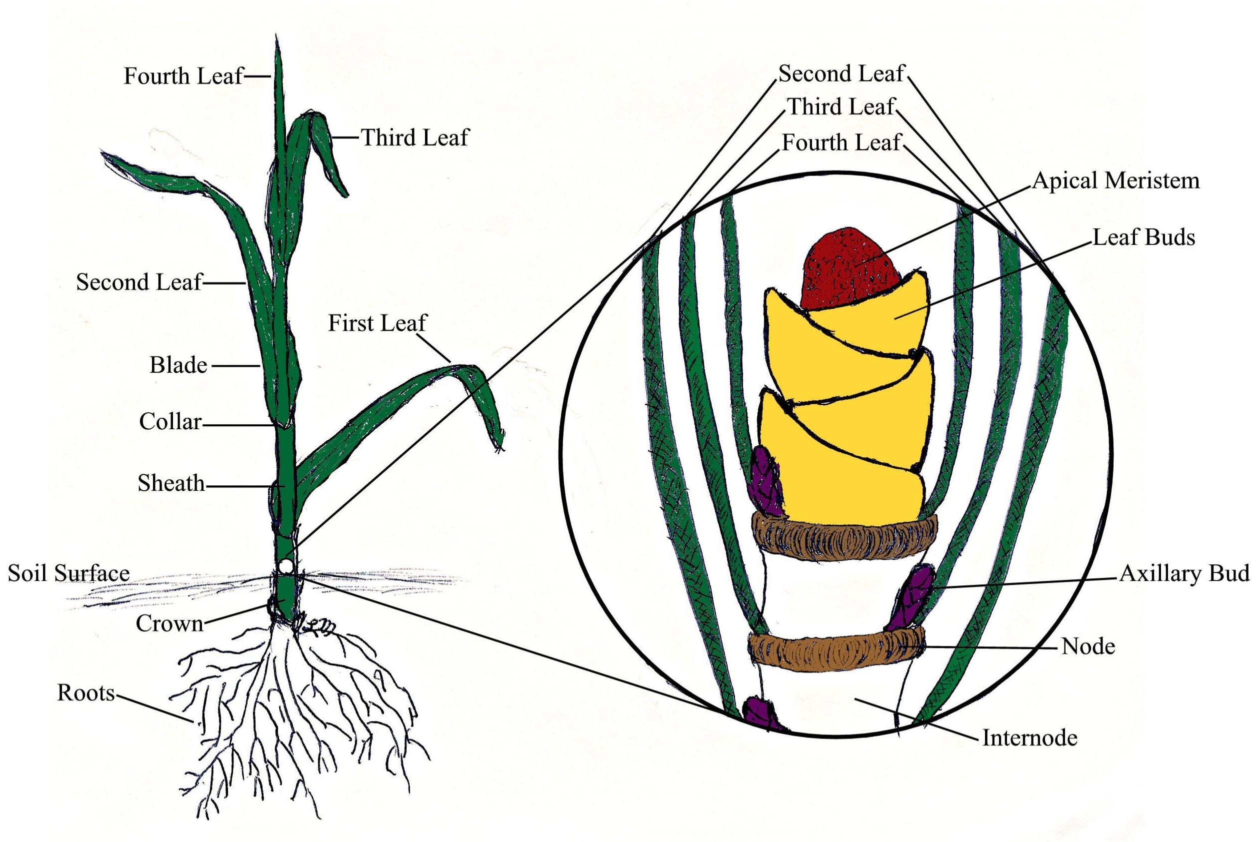
Native warm season grasses start early leaf greenup of vegetative carryover tillers in mid May, have crude protein levels above 15%, reach 44% of the leaf growth in height by early June, containing crude protein above 13% during early to mid June. Most warm season grasses reach the 3.5 new leaf stage around mid June, reaching 85% of the leaf growth in height by late June and reach 100% of height by late July. Seed stalks begin to develop in mid June and reach the flower stage after 21 June with 12.2% crude protein. During the seed development stage, crude protein levels remain above 9.6% until late July when the flower stalks reach 91% of the growth in height. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During mid August, crude protein levels drop below 7.0%, seed stalks reach 100% of the growth in height by late August when the seeds are mature and being shed, and drop below 6.0% in crude protein by early September (Whitman et al. 1951, Goetz 1963, Manske 2000c, 2008b). Crude protein levels of warm season secondary tillers increase above 9.0% during August to 10.0% in early September, decreases during September, and drop below 9.6% in late September (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late August, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Crude protein levels of upland sedges do not follow the same relationship with phenological growth stages as in cool and warm season grasses.

Crude protein levels in upland sedges remain high through the flower and seed mature stages. Upland sedges grow very early and produce seed heads in late April to early May and crude protein remains above 9.6% until mid July. Crude protein levels decrease with increases in senescence and drop below 7.8% in early August but do not fall below 6.2% for the remainder of the growing season (Whitman et al. 1951, Manske 2008b). Phosphorus levels drop below 0.18% in mid May when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

The quality of grass forage available to grazing graminivores on grasslands of the Northern Plains is above 9.6% crude protein in the lead tillers of the cool and warm season grasses during mid May to late July. Upland sedges have crude protein levels above 9.6% during early May to mid July. The secondary tillers of the cool and warm season grasses have crude protein levels above 9.6% during mid July to late September or mid October.

The early greenup of rangeland grass in the spring is not from new seedlings but from vegetative carryover tillers that did not produce a seedhead during the previous growing season. Spring growth of carryover tillers depends both on carbohydrate reserves and on photosynthetic products from the portions of previous years leaves that overwintered without cell wall rupture and regreened with chlorophyll. Grass tiller growth and development depend, in part, on some carbohydrate reserves in early spring because the amount of photosynthetic product synthesized by the green carryover leaves and the first couple of early growing new leaves is insufficient to meet the total requirements for leaf growth (Coyne et al. 1995). Grass growth also requires that the tiller maintains adequate leaf area with a combination of carryover leaves and new leaves to provide photosynthetic product for growth of sequential new leaves. The total nonstructural carbohydrates of a grass tiller are at low levels following the huge reduction of reserves during the winter respiration period, and the carbohydrate reserves remaining in the roots and crowns are needed for both root growth and initial leaf growth during early spring. The low quantity of reserve carbohydrates are not adequate to supply the entire amount required to support root growth and also support leaf growth causing a reduction in active growth until sufficient leaf area is produced to provide the photosynthetic assimilates required for plant growth and other processes (Coyne et al. 1995). Removal of aboveground leaf material from grass tillers not yet at the three and a half new leaf stage deprives tillers of foliage needed for photosynthesis and increases the demand upon already low levels of carbohydrate reserves.



Grass Tiller at 3.5 Leaf Stage

Figure 1. Grass Tiller Structures.

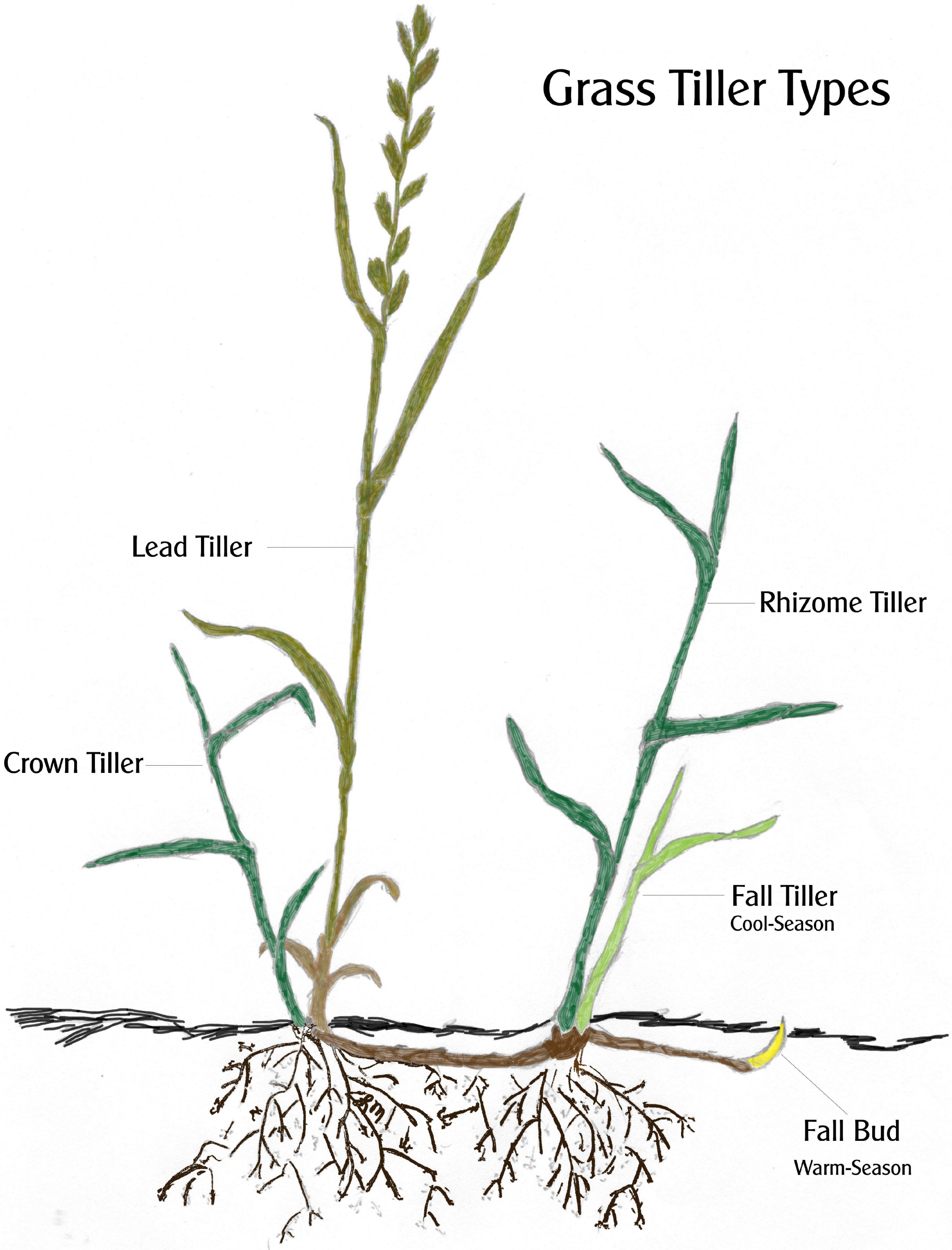


Figure 2. Vegetative Reproduction by Tillering.

1983-2012 Study of Grass Vegetation Weight Performance

Management Treatments

A 30 year study evaluated herbage weight performance during 6 monthly periods from May to October on native rangeland pastures managed by two distinctly different concepts. The traditional concept managed the land for its use as forage for livestock. The biologically effective concept managed the land as an ecosystem that considers the biological requirements of the grass plants, soil microbes, and the livestock.

Native Rangeland Pastures

The traditional concept was used to manage one native rangeland pasture (replicated two and three times during various periods) with a seasonlong system stocked with 7 cows/80 acres at 11.43 ac/AU and 2.60 ac/AUM for 4.5 months from 1 June to 15 October (137 days).

The biologically effective concept was used to manage three native rangeland pastures (replicated two times) with a twice-over rotation system stocked with 8 cows/80 acres at 10.22 ac/AU and 2.30 ac/AUM for 4.5 months from 1 June to 15 October (137 days).

Domesticated Graminivores

Commercial cow-calf pairs grazed the native rangeland pastures during this study. During 1983 to 1994, commercial Angus-Hereford cows with Charolais sired calves were used. These cows were assigned to separate herd pools for each grazing treatment. During 1995 to 2012, commercial crossbred cattle were used on all grazing treatments. Before spring turn out cow-calf pairs were sorted by cow age, and calf age with 50% steers and heifers.

Precipitation

The precipitation in inches and percent of long-term mean for perennial plant growing season months, April to October, and growing season months with water deficiency conditions are reported in the study introduction (Manske 2016). The 12 year period of 1983 to 1994 had a total of 72 growing season months, 31 months (43.1%) had water deficiency conditions, 14.5 months (20.1%) had high precipitation greater than 125% of LTM, and 26.5 months (36.8%) had normal precipitation greater than 75% and less than 125% of LTM. The 11 year period of 1995 to 2005 had a total of 66 growing season months, 15.5 months (23.4%) had water deficiency conditions, 27.5 months (41.7%) had high precipitation greater than 125% of LTM, and 23.0 months (34.8%) had normal precipitation greater than 75% and less than 125% of LTM. The 7 year period of 2006 to 2012 had a total of 42 growing season months, 13.5 months (32.1%) had water deficiency conditions, 11.0 months (26.2%) had high precipitation greater than 125% of LTM, and 17.5 months (41.7%) had normal precipitation greater than 75% and less than 125% of LTM.

Procedures

The effects on native rangeland grass vegetation from partial defoliation by grazing graminivores managed by the biologically effective concept was compared to that managed by the traditional concept. Changes in aboveground herbage biomass and % basal cover were evaluated with data collected during the growing season, May to October, from 1983 to 2012.

Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986). Vegetation on the grazed areas of each destructive sampling site was protected from grazing during one growing season by steel wire quonset type cages measuring 3 X 7 foot, which were moved to a new location each year prior to livestock turnout. The vegetation samples collected from the protective cages was labeled ungrazed during that growing season, however, the vegetation was grazed during all the years of the study except during the single year that the vegetation was protected from grazing by the placement of a cage. The herbage material from five 0.25 m^2 quadrats (frames) at each sample site from inside the cages (ungrazed) was hand clipped to ground level and sorted in the field by standard biotype categories: cool season, warm season, upland sedges, forbs, standing dead, and litter (the standing dead and litter categories were not included) only the living biomass was included in this report. 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. The mean monthly herbage biomass in lbs/ac for each biotype category of each year was replicated with n = 10 or 15 for the traditional concept and n = 15 or 30 for the biologically effective concept.

During May to August of the first four growing seasons of the study, the number of biotype categories were increased to only include one or two major plant species: Cool short (Prairie Junegrass and Plains reedgrass), Cool middle (Needle and Thread and Green needlegrass), Wheatgrass (Western and Thickspike wheatgrass), Warm short (Blue grama), Upland sedge (Threadleaf and Needleleaf sedges), and Forbs (all forbs). An additional category of Warm tall (Prairie sandreed) was collected on the sandy sites. Mean herbage biomass of biotype during the grazing period (June, July, and August) were determined. Herbage biomass data collected during September and October were placed in standard biotype categories. The data from the initial four years were further sorted into years 1-2 and years 3-4. The differences in herbage biomass production during these two 2 year periods should show the effects from the biologically effective management on the numerous biotype categories on the sandy, shallow, and silty ecological sites.

Plant species % basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986), with 2000 points collected along long-term transect lines outside (grazed) of each exclosure. Basal cover data of each plant species were sorted into standard biotype categories: cool season, warm season, and upland sedge. Basal cover for each biotype category of each year was replicated with n = 2 or 3 for the traditional concept and n = 3 or 6 for the biologically effective concept.

The evaluation of herbage biomass production and basal cover for graminoids on the biologically effective concept pastures compared to that on the traditional concept pastures during the entire 30 year study period, 1983 to 2012, used the standard biotype categories from the silty ecological sites.

Results

The traditional concept and the biologically effective concept were managed to have grazing periods that occurred at the same time, with the same number of days and number of months grazed.

The traditional concept for management of the seasonlong grazing strategy was developed to provide forage to grazing graminivores without consideration of the biological requirements of the grass plants and soil microbes, and did not consider the crude protein requirements of the cows. The single native rangeland pasture of the seasonlong system was grazed one time during the 4.5 month period from early June to mid October (137 days).

The biologically effective concept for management of the twice-over rotation grazing strategy was developed to coordinate partial defoliation events with grass phenological growth stages, meet the biological requirements of the grass plants and rhizosphere organisms, meet the nutritional requirements of the grazing graminivores, and enhance the ecosystem biogeochemical processes and activate the internal grass plant growth mechanisms to function at potential levels. Each of the three native rangeland pastures of the twice-over rotation system were grazed two times during the 4.5 month period from early June to mid October. The first grazing period of 15 days occurred between 1 June and 15 July, when grass lead tillers were between the three and a half new leaf stage and the flower stage. The second grazing period of 30 days occurred after 15 July and prior to mid October, when the stimulated vegetative secondary tillers had reached their three and a half new leaf stage. The first pasture grazed each year was the last pasture grazed the previous year. A three year sequence would be ABC, CAB, and BCA.

Initial four years, 1983-1986

The four year period of 1983 to 1986 had a total of 24 growing season months, 7.0 months (29.2%) had water deficiency conditions, 6.0 months (25.0%) had high precipitation greater than 125% of LTM, and 11.0 months (45.8%) had normal precipitation greater than 75% and less than 125% of LTM (Manske 2016).

During the first four years (1983-1986), herbage biomass data was collected with an increased number of biotype categories in order to follow the initial changes in the major grasses that resulted from the effects of the twice-over rotation strategy. Data for years 1-2 and years 3-4 for the sandy, shallow, and silty ecological sites are shown in tables 1, 2, and 3, respectively. The herbage biomass produced by the major grass and upland sedge species all had greatly increased during years 3-4 (tables 1, 2, and 3). The herbage biomass produced by the forb species decreased during years 3-4 (tables 1, 2, and 3).

Compared to the herbage biomass produced during years 1-2, the mean increase in herbage biomass produced on the sandy, shallow, and silty sites during years 3-4 was 196.93 lbs/ac for warm short, 121.92 lbs/ac for cool mid, 115.14 lbs/ac for upland sedge, 78.98 lbs/ac for cool short, 37.60 lbs/ac for wheatgrass, and 31.87 lbs/ac for warm tall, for a mean total increase of 582.44 lbs/ac for herbage biomass. The herbage biomass increase was 751.95

lbs/ac on the silty site, 545.68 lbs/ac on the sandy site, and 449.67 lbs/ac on the shallow site (tables 4, 5, and 6). A mean total loss of biomass was 37.00 lbs/ac for the forbs, the loss was 43.28 lbs/ac on the shallow site, 34.03 lbs/ac on the sandy site, and 33.69 lbs/ac on the silty site (tables 4, 5, and 6).

During years 3-4, the twice-over strategy increased herbage biomass production 32.5% for the grasses, 49.6% for the upland sedges, and decreased forb biomass 18.6% on the sandy site, increased herbage biomass production 65.7% for the grasses, 22.6% for the upland sedges, and decreased forb biomass 20.2% on the shallow site, and increased herbage biomass production 63.1% for the grasses, 64.7% for the upland sedges, and decreased forb biomass 13.2% on the silty site (tables 4, 5, and 6).

The total herbage biomass production was 31.5% greater on the sandy site, 40.1% greater on the shallow site, and 49.7% greater on the silty site during years 3-4 than the total production during years 1-2 (tables 4, 5, and 6).

Western wheatgrass and blue grama are both important grasses of the Northern Mixed Grass Prairie. Western wheatgrass is much taller than blue grama, however, blue grama usually has greater basal cover. Both grasses increase herbage biomass production when grazed using the twice-over treatment. During years 3-4, western wheatgrass increased biomass 71.9% and blue grama increased biomass 116.3%. Mean herbage biomass during June to August produced by western wheatgrass was 55.11, 37.27, and 212.10 lbs/ac on the sandy, shallow, and silty sites, respectively. Blue grama produced 184.48, 382.77, and 606.93 lbs/ac on the sandy, shallow, and silty sites, respectively. Blue grama outproduced western wheatgrass 234.8%, 927.0%, and 186.2% on the sandy, shallow, and silty sites, respectively (tables 1, 2, and 3, the separately collected wheatgrass data is with the cool middle grasses in table 1).

The great increase in herbage biomass for the grasses and upland sedges that occurred during years 3-4 on the sandy, shallow, and silty ecological sites was the result of belowground changes that started during years 1-2. Prior to 1983, the grassland was managed with seasonlong grazing. The biomass of the rhizosphere organisms was low and their low activity of mineralization of organic nitrogen had caused a deficiency in the availability of mineral nitrogen. The grass plant growth mechanisms: compensatory physiological mechanism, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency all require a minimum threshold level of 100 lbs/ac of available mineral nitrogen to function properly. The partial defoliation by the grazing graminivores that removed 25% to 33% of grass lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage caused increased quantities of short chain carbon energy to be released from the tillers and exudated through the roots into the rhizosphere. The rhizosphere organisms are achlorophyllous and depend on short chain carbon energy from the grass plants at vegetative growth stages in quantities greater than the leakage rate. This process started building the rhizosphere microbe biomass during the first two years of the study. During the years 3-4, the rhizosphere biomass had increased to a sufficient quantity great enough to mineralize adequate quantities of mineral nitrogen that could support the functioning of the grass plant mechanisms. The grass plant growth mechanisms require activation which is also the partial defoliation by grazing graminivores that removed 25% to 33% of grass lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage which occurs from 1 June to mid July each growing season. Activation plus an adequate supply of mineral nitrogen is required for the grass plant growth mechanisms to function. The combination of increasing the rhizosphere microbe biomass, the mineralization of adequate quantities of mineral nitrogen, and the activation of the grass plant growth mechanisms required two full growing seasons to show effects in aboveground herbage production resulting in the great increase in grass herbage biomass production during years 3-4. The reference rhizosphere weight of 406.44 kg/m^3 was measured during year 24. The maximum weight obtainable is still unknown. However, rhizosphere weights at slightly greater than 50% of the reference weight are able to mineralize 99.35 lbs/ac of mineral nitrogen. Rhizosphere weights at less than 50% of the reference weight are unable to mineralize adequate quantities of mineral nitrogen.

The increase in biomass of both endomycorrhizal fungi and ectomycorrhizal fungi greatly increase the amounts of secreted insoluble extracellular adhesive polysaccharides that form water-stable aggregates in the soil that are water permeable but not water soluble, and the increased soil aggregation improves soil quality, increases soil oxygenation, increases water infiltration, and increases water holding capacity (Harley and Smith 1983, Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat

2003). Improvement of water infiltration and enlargement of the water holding capacity increases the effectiveness of the precipitation received, increases the quantity of soil water available for plant and soil microbe growth, and reduces plant growth problems between rain events. This improvement in soil quality is conducive to greater herbage biomass production.

Thirty years, 1983-2012

The 30 year period of 1983 to 2012 had a total of 180 growing season months, 60.0 months (33.3%) had water deficiency conditions, 53.0 months (29.4%) had high precipitation greater than 125% of LTM, and 67.0 months (37.2%) had normal precipitation greater than 75% and less than 125% of LTM (Manske 2016).

Thirty years, 1983 to 2012, of monthly herbage biomass and % basal cover data for standard biotype categories has been collected to evaluate effects on grass vegetation on the silty ecological sites from the biologically effective concept of management compared to the effects from the traditional concept of management. Thirty years of annual mean monthly herbage biomass (lbs/ac) by four standard biotype categories for the biologically effective concept (Appendix tables 1-4) and the traditional concept (Appendix tables 5-8) were summarized into 30 year means (tables 7 and 8 and figures 3 and 4).

The mean monthly herbage biomass values for the cool and warm season grasses on the biologically effective concept were greater than those on the traditional concept (tables 7 and 8 and figures 3 and 4). The mean monthly herbage biomass values for the upland sedges and forbs on the biologically effective concept were lower than those on the traditional concept, except the mean October upland sedge herbage weight was 10.66 lbs/ac greater on the biologically effective concept than that on the traditional concept (tables 7 and 8 and figures 3 and 4).

The cool season grasses on the biologically effective concept (table 7 and figure 3) produced a great lead tiller peak of 760.51 lbs/ac in July and then produced a greater secondary vegetative tiller peak of 826.89 lbs/ac in September. The secondary vegetative tillers were at growth stages greater than the three and a half new leaf stage and contained similar nutrient quality as the lead tillers had at the same growth stages. The cool season grasses on the traditional concept (table 8 and figure 4) produced a 20.3% lower lead tiller peak of 606.10 lbs/ac in July and than produced a 33.6% lower secondary vegetative tiller peak of 548.70 lbs/ac in September. The warm season grasses on the biologically effective concept (table 7 and figure 3) produced a lead tiller peak of 333.21 lbs/ac in August which is 16.1% greater than the lead tiller peak of 287.08 lbs/ac produced in August on the traditional concept (table 8 and figure 4).

The herbage biomass production of upland sedge on the silty site of the biologically effective concept increased 64.7% during years 3-4 compared to that during years 1-2 (table 6). After 30 years of treatment, the upland sedge herbage biomass on the biologically effective concept was produced at a 12.4% lower mean weight than that produced on the traditional concept (tables 9 and 10). The peak upland sedge biomass in July on the biologically effective concept was 204.99 lbs/ac (table 7 and figure 3) which was 13.8% lower than the peak upland sedge biomass in July at 237.83 lbs/ac on the traditional concept (table 8 and figure 4). During the initial stages after implementation of the biologically effective management concept, the upland sedge component greatly increased filling bare spaces in the plant community. The ecosystem continued to improve and develop. Around year 15, the cool and warm season grasses increased into the upland sedge areas and the upland sedges started to decrease.

The herbage biomass production of forbs on the silty site of the biologically effective concept decreased 13.2% during years 3-4 compared to that during years 1-2 (table 6). After 30 years of treatment, the forb herbage biomass on the biologically effective concept was produced at a 28.6% lower mean weight than that produced on the traditional concept (tables 9 and 10). The peak forb biomass in July on the biologically effective concept was 193.27 lbs/ac (table 7 and figure 3) which was 34.2% lower than the peak forb biomass in July at 293.73 lbs/ac on the traditional concept (table 8 and figure 4).

There is a huge biological advantage for grass plants to grow in an ecosystem that has the biogeochemical processes performed by the rhizosphere microbes functioning at potential levels and the four main grass plant growth mechanisms functioning with adequate quantities of available essential elements which are all made possible by the beneficial effects from the biologically effective twice-over rotation strategy. Greater quantities of live cool and warm season grasses are available during the entire grazing period from 1 June to 15

October. The cool season peak herbage biomass occurs in July. The peak on the traditional concept comes within 25.5% of the peak on the biologically effective concept which was the closest that the herbage weight on the two concepts came together (table 9). During June, the live cool season herbage biomass was 31.8% greater on the biologically effective concept. During August, September, and October, the live cool season herbage biomass was 36.5% greater on the biologically effective concept (table 9). The warm season peak herbage biomass occurs in August. The peak on the traditional concept came within 16.1% of the peak on the biologically effective concept which was the closest that the herbage weight on the two concepts came together (table 9). During June and July, the live warm season herbage was 31.1% greater on the biologically effective concept. During September and October, the live warm season herbage was 30.2% greater on the biologically effective concept (table 9).

During the period from mid July to mid October, traditionally managed pastures are usually deficient of adequate quantity and quality of grass forage. The mean July to October cool and warm season herbage biomass on the traditional concept was 802.05 lbs/ac. The mean July to October cool and warm season herbage biomass on the biologically effective concept was 1049.36 lbs/ac which provided 30.8% greater live grass forage containing abundant quantities of nutrients on the pastures managed by the biologically effective concept during the problem time period. This is the reason that cow and calf weight performance on the biologically effective concept is superior to that on the traditional concept.

The upland sedge peak herbage biomass occurs in July. The peak biomass on the biologically effective concept was 13.8% lower than the peak biomass on the traditional concept (table 9). During June, the upland sedge herbage biomass was 11.9% lower on the biologically effective concept than that on the traditional concept. During August, September, and October, the upland sedge herbage biomass was 13.7% lower on the biologically effective concept than that on the traditional concept (table 9).

The forb peak herbage biomass occurs in July. The peak biomass on the biologically effective concept was 34.2% lower than the peak biomass on the traditional concept (table 9). During June, the forb biomass was 32.9% lower on the biologically effective concept than that on the traditional concept. During August, September, and October, the forb herbage biomass was 24.7% lower on the biologically effective concept than that on the traditional concept (table 9).

Compared to the 30 year mean grass herbage biomass produced on the traditional concept, the grass herbage biomass produced on the biologically effective concept was 240.47 lbs/ac (31.2%) greater, the cool season biomass was 179.56 lbs/ac (33.3%) greater, and the warm season biomass was 60.91 lbs/ac (26.4%) greater (table 10). Compared to the 30 year mean grass percent basal cover produced on the traditional concept, the grass percent basal cover produced on the biologically effective concept was 8.36% (57.2%) greater, the cool season percent basal cover was 1.17% (20.0%) greater, and the warm season percent basal cover was 7.19% (82.1%) greater (table 11). On the biologically effective concept, the grass composition was 74.9% of the total live herbage biomass (table 10) and was 80.5% of the total basal cover (table 11). The composition of the cool season grass was 53.3% of the herbage biomass and 24.6% of the basal cover (tables 10 and 11). The composition of the warm season grass was 21.6% of the herbage biomass and 55.9% of the basal cover (tables 10 and 11).

Compared to the 30 year mean upland sedge herbage biomass and percent basal cover produced on the traditional concept, the upland sedge on the biologically effective concept had 24.0 lbs/ac (12.4%) lower herbage biomass and had 0.4% (6.7%) lower basal cover (tables 10 and 11). On the biologically effective concept, the upland sedge composition was 12.5% of the herbage biomass and 19.5% of the total basal cover (tables 10 and 11).

Compared to the 30 year mean forb herbage biomass produced on the traditional concept, the forbs on the biologically effective concept had 68.22 lbs/ac (28.6%) lower herbage biomass (table 10). On the biologically effective concept, the forb composition was 12.6% of the total herbage biomass (table 10).

Blue grama and upland sedges usually do not get credit for the ecological service they perform as protectors of the soil by reducing soil erosion, reducing soil temperature, reducing soil water evaporation, and reducing bare spots which reduces place for invasion of undesirable plants and pestiferous grasshoppers. On the tradition concept, blue grama and upland sedges have a basal cover of 14.7% with a composition of 71.6% (table 11). On the biologically effective concept, blue grama and upland sedge have a basal cover 46.3% greater at 21.5% with a composition of 75.4% (table 11). Both blue grama and upland sedges are extremely important plants in the Mixed Grass Prairie of the Northern Plains.

Vegetative Reproduction by Tillering

Increasing herbage biomass on grasslands requires full activation of the four primary internal plant mechanisms that help grass tillers withstand and recover from partial defoliation by grazing. The primary internal mechanisms are: compensatory physiological mechanisms (McNaughton 1979, 1983; Briske 1991); vegetative reproduction by tillering (Mueller and Richards 1986; Richards et al. 1988; Murphy and Briske 1992; Briske and Richards 1994, 1995); nutrient resource uptake (Crider 1955; Li and Wilson 1998; Kochy and Wilson 2000; Peltzer and Kochy 2001); and water use efficiency (Wight and Black 1972, 1979). The required initial step must be to raise the rhizosphere organism biomass to levels capable of mineralizing a threshold level of 100 lbs/ac (112/kg) or greater of available mineral nitrogen (Wight and Black 1972, 1979). Rhizosphere organisms are limited by accessing energy in the form of short carbon chains. Carbon energy can be released from grass lead tillers throught the roots into the rhizosphere by removal of 25% -33% of the aboveground leaf biomass by large grazing graminivores when the lead tillers are at the phenological growth stages between the three and a half new leaf stage and the flower (anthesis) stage during early June to mid July (Manske 1999, 2011b, 2014c). Full activation of internal grass plant mechanisms requires mineral nitrogen to be available at 100 lbs/ac (112 kg/ha) (Wight and Black 1972, 1979; Manske 2010 a,b). It also requires available carbon fixed through photosynthesis from 67% to 75% of the leaf area of predefoliated lead tillers before the flower stage (Manske 2010 a,b) and from 50% of the leaf area after the flower stage (Crider 1955). An increase in available mineral nitrogen and the other essential elements permits the grass tillers to synthesize increasing quantities of carbohydrates, proteins, and nucleic acids to accelerate growth rates of replacement leaves and shoots, increase photosynthetic capacity of remaining mature leaves, increase secondary tiller development from axillary buds, enhance the competitiveness of nutrient resource uptake, and improve water use efficiency. The combination of increased ecosystem biogeochemical processes and improved functioning of the internal grass plant mechanisms results in increases in grass herbage production and in plant density (basal cover) of the desirable grass species. Changes in the aboveground vegetation lag behind changes in the soil microorganism biomass and activity when a grassland ecosystem is degrading and also when it is aggrading.

Vegetative Tiller Study

Stimulation of vegetative reproduction of the grass tillering mechanisms is the primary factor needed to increase herbage biomass production on grasslands. Increasing the quantity and quality of grass herbage biomass by increasing grass tiller density is the key to improving livestock performance and increasing economic value captured per acre (hectare) from grasslands. The mechanisms of vegetative reproduction of secondary tillers from axillary buds are not a simple stimulus-response reaction. Activation of vegetative tillers can only occur at lead tiller vegetative phenological stages between the three and a half new leaf stage and the flower (anthesis) stage by partial defoliation by grazing graminivores that remove 25%-33% of aboveground leaf material with a minimum of a threshold quantity of 100 lbs/ac (112 kg/ha) of available mineral nitrogen and the quantity of available carbon fixed through photosynthesis from 67% to 75% of the predefoliated lead tiller leaf area. The quantity of herbage biomass is determined by grass tiller height and density. Grass tiller height is set by grass species genetics and the quantity of soil water. When grass leaf heights are similar, the management strategy that supports the greatest tiller density will produce the greatest quantity of herbage biomass.

A study that evaluated the differences in the quantity of secondary tillers produced vegetatively on the traditional seasonlong and the biologically effective twice-over rotation strategies with 25% leaf removal in mid June compared to a control of 0% leaf removal was conducted during the growing seasons of 2000 and 2001.

The grass tillers were classified by age and rate of growth. Lead tillers had rapid or unimpeded growth. Reproductive lead tillers developed into sexually reproductive stages. Vegetative lead tillers remained vegetative to the end of the growing season. Secondary tillers were initiated during the spring or summer and had inhibited growth rates regulated by a lead tiller. Secondary tillers could be held at the 2 or 3 leaf stage for long periods of time. Slow growth secondary tillers remained vegetative to the end of the growing season. Early senescent secondary tillers terminated growth prematurely before development of more than the 4 leaf stage during the growing season. Fall secondary tillers were cool season grass tillers initiated between mid August and mid October.

Carryover tillers maintained intact apical meristem, survived the winter period, and resumed growth and development the following growing season as lead tillers.

Procedures

The same grazing management treatments and cow-calf pairs of the 1983-2012 Study were used during the Vegetative Tiller Study. At the start of the vegetative tiller study, the grazing management strategies had continuous operation of 14 years for the traditional seasonlong and 17 years for the twice-over rotation system. Study site exclosures 16' X 32' (4.9 m X 9.8 m) made of stock panels were located on silty ecological sites on a gently sloping upland landscape with deep fine sandy loam soils. Seven randomly placed microplots composed each defoliation treatment. The microplots were PVC conduit barrier with a 3 inch (7.62 cm) diameter and 6 inch (15.24 cm) depth that were open at both end were inserted into the soil. Western wheatgrass was selected as the model species for vegetative tiller development. Every tiller within each microplot was identified with a different distinguishing loop of colored wire that encircled the tiller at its base. New tillers were identified by colored wire as they developed and carryover tillers were remarked at the start of the second year. The defoliation treatments included in this report are the control of 0% defoliation and mid June 25% defoliation treatments. The data collected biweekly for each tiller included number of leaves produced, phenological growth stage, and height of leaves. From these data determination of tiller density, tiller dynamics, tiller initiation, tiller termination, tiller growth and development, and dynamics of forage tiller density was possible.

Results

The two year period of 2000 to 2001 had a total of 12 growing season months, 3.5 months (29.2%) had water deficiency conditions, 3.5 months (29.2%) had high precipitation greater than 125% of LTM, and 5.0 months (41.7%) had normal precipitation greater than 75% and less than 125% of LTM (Manske 2016).

The entire vegetative tillering study included additional partial defoliation treatments that were detrimental to tiller growth. The treatments of mid May 25%, mid May 50%, and mid June 50% leaf removal resulted in substantially less tiller development than the tiller development on the control of 0% leaf removal.

Partial defoliation of mid May 25% and mid May 50% occurred before the tillers reached the three and a half new leaf stage and was extremely detrimental to tiller growth on all grazing management strategies. The combination of carryover leaf area and the remaining new leaf area after partial defoliation was insufficient to produce adequate quantities of nonstructural carbohydrates to support complete replacement of removed leaf area resulting in greatly reduced growth rates of herbage production with very few new tiller initiations during the growing season. The results from partial defoliation before the three and a half new leaf stage were similar to the results of previous partial defoliation treatments before the three and a half new leaf stage at Swift Current, Mandan, and Dickinson (table 12) (Campbell 1952, Rogler et al. 1962, Manske 2008c) and the reduced herbage production growth rates reported by Coyne et al. (1995).

Partial defoliation of mid June 50% occurred after the tillers had reached the three and a half new leaf stage but before the tillers had reached full leaf height development. The regreened carryover leaves had mostly senesced. The remaining new leaf area after partial defoliation of 50% was insufficient to produce adequate quantities of nonstructural carbohydrates to support complete replacement of removed leaf area on all grazing management strategies. The seasonlong management strategy had a low volume of rhizosphere microbes that mineralized nitrogen at below threshold levels of 112 kg/ha (100 lbs/ac) resulting in extremely low secondary tiller initiation (table 13). The twice-over management strategy had a high volume of rhizosphere microbes that mineralized nitrogen at levels greater than the threshold level of 112 kg/ha resulting in secondary tiller initiation similar to that of the control with 0% leaf removal (table 13). This reduction in secondary tiller development was caused by inadequate leaf area to fix the needed quantity of carbon. The remaining leaf area during the lead tiller vegetative stages between the three and a half new leaf stage and the flower stage needs to be between 67% to 75% of the predefoliated lead tiller leaf area. The amount of leaf area that can be removed is 25% to 33%. At this level, the partial defoliation removes sufficient quantities of auxin and stimulates the vegetative tillering mechanisms while retaining adequate quantities of new leaf area than can fix sufficient quantities of nonstructural carbohydrates to support complete replacement of removed leaf area and also support growth and development of the activated secondary tillers from axillary buds.

Tiller Density

Control Treatment

A total of 845.8/m^2 different tillers were present on the control treatment of the traditional seasonlong management strategy during two growing seasons (table 14), of which 188.0/m^2 were carryover tillers the first year and 657.8/m^2 were new initiated vegetative tillers. A total of 250.6/m^2 vegetative tillers terminated prematurely and 125.3/m^2 lead tillers terminated after flowering, resulting in 469.9/m^2 tillers remaining mid October at the end of the second growing season.

A total of 2098.8/m^2 different tillers were present on the control treatment of the twice-over management strategy during two growing seasons (table 14), of which 626.5/m^2 were carryover tillers the first year and 1472.3/m^2 were new initiated vegetative tillers. A total of 720.4/m^2 vegetative tillers terminated prematurely and 720.5/m^2 lead tillers terminated after flowering, resulting in 657.9/m^2 tillers remaining mid October at the end of second growing season.

Mid June 25% Treatment

A total of 908.5/m^2 different tillers were present on the mid June 25% defoliation treatment of the traditional seasonlong management strategy during two growing seasons (table 14), of which 250.6/m^2 were carryover tillers the first year and 657.9/m^2 were new initiated vegetative tillers. A total of 313.3/m^2 vegetative tillers terminated prematurely and 219.3/m^2 lead tillers terminated after flowering, resulting in 375.9/m^2 tillers remaining mid October at the end of the second growing season.

A total of 2255.6/m^2 different tillers were present on the mid June 25% defoliation treatment of the twice-over management strategy during two growing seasons (table 14), of which 595.2/m^2 were carryover tillers the first year and 1660.4/m^2 were new initiated vegetative tillers. A total of 877.2/m^2 vegetative tillers terminated prematurely and 344.6/m^2 lead tillers terminated after flowering, resulting in 1033.8/m^2 tillers remaining mid October at the end of second growing season.

The mid June 25% treatment of the seasonlong management strategy had 7.4% more total different tillers, 0.0% more initiated tillers, 41.7% more terminated tillers, and 20.0% fewer remaining tillers than that on the control treatment of the seasonlong management strategy (table 14). The mid June 25% treatment of the twice-over management strategy had 7.5% more total different tillers, 12.8% more initiated tillers, 15.2% fewer terminated tillers, and 57.1% more remaining tiller than that on the control treatments of the twice-over management strategy (table 14).

The control treatment of the twice-over management strategy had 148.1% more total different tillers, 123.8% more initiated tillers, 283.3% more terminated tillers, and 40.0% more remaining tillers than that on the control treatment of the seasonlong management strategy (table 14). The mid June 25% treatment of the twice-over management strategy had 148.3% more total different tillers, 152.4% more initiated tillers, 129.4% more terminated tillers, and 175.0% more remaining tillers than that on the mid June 25% treatment on the seasonlong management treatment (table 14).

Tiller Dynamics

Control Treatment

The first year on the control treatment of the traditional seasonlong management strategy (table 15, figure 5) started in early May with 281.9 /m^2 vegetative tillers including 188.0 /m^2 lead tillers and 94.0 /m^2 secondary tillers. Assuming the lead tillers were carry over tillers from the previous growing season. Vegetative reproduction produced 0.0 /m^2 tillers during the first growing season with 0.0 /m^2 initiated during May and 0.0 /m^2 initiated during mid season. A total of 281.9 /m^2 different tillers were present during the first growing season. During mid season, 94.0 /m^2 lead tillers developed into reproductive flowering stages (33.3% of the tiller population). Before reaching maturity, 62.7 /m^2 vegetative tillers terminated. Between mid August and mid October, 94.0 /m^2 fall tillers developed. During mid October, 219.3 /m^2 live vegetative tillers remained, of which, 94.0 /m^2 were lead tillers, 31.3 /m^2 were secondary tillers, and 94.0 /m^2 were fall tillers. During the winter period, 0.0 /m^2 tillers terminated. The second year on the control treatment (table 15, figure 5) started in early May with 407.2 /m^2 vegetative tillers including 219.3 /m^2 lead tillers and 188.0 /m^2 secondary tillers, of which, 219.3 /m^2 were carry over tillers and 188.0 /m^2 were early spring initiated tillers; there were 125.3 /m^2 more tillers than during May of the first growing season. Vegetative reproduction produced 125.3 /m^2 tillers during the second growing season with 31.3 /m^2 initiated during May and 94.0 /m^2 initiated during mid season. A total of 532.5 /m^2 different tillers were present during the second growing season; there were

250.6 /m^2 more total tillers than during the first growing season. During mid season, 31.3 /m^2 lead tillers developed into reproductive flowering stages (5.9% of the tiller population). Before reaching maturity, 188.0 /m^2 vegetative tillers terminated. Between mid August and mid October, 156.6 /m^2 fall tillers developed. During mid October, 469.9 /m^2 live vegetative tillers remained, of which, 219.3 /m^2 were lead tillers, 94.0 /m^2 were secondary tillers, and 156.6 /m^2 were fall tillers; there were 250.6 /m^2 more live vegetative tillers than during mid October of the first growing season.

The first year on the control treatment of the twice-over rotation management strategy (table 15, figure 5) started in early May with 877.1 /m^2 vegetative tillers including 626.5 /m^2 lead tillers and 250.6 /m^2 secondary tillers. Assuming the lead tillers were carry over tillers from the previous growing season. Vegetative reproduction produced 62.7 /m^2 tillers during the first growing season with 31.3 /m^2 initiated during May and 31.3 /m^2 initiated during mid season. A total of 939.8 /m^2 different tillers were present during the first growing season. During mid season, 344.6 /m^2 lead tillers developed into reproductive flowering stages (36.7% of the tiller population). Before reaching maturity, 250.6 /m^2 vegetative tillers terminated. Between mid August and mid October, 250.6 /m^2 fall tillers developed. During mid October, 595.2 /m^2 live vegetative tillers remained, of which, 219.3 /m^2 were lead tillers, 125.3 /m^2 were secondary tillers, and 250.6 /m^2 were fall tillers. During the winter period, 31.3 /m^2 tillers terminated. The second year on the control treatment (table 15, figure 5) started in early May with 1033.8 /m^2 vegetative tillers including 626.5 /m^2 lead tillers and 407.2 /m^2 secondary tillers, of which, 563.9 /m^2 were carry over tillers and 469.9 /m^2 were early spring initiated tillers; there were 156.6 /m^2 more tillers than during May of the first growing season. Vegetative reproduction produced 250.6 /m^2 tillers during the second growing season with 125.3 /m^2 initiated during May and 125.3 /m^2 initiated during mid season. A total of 1284.4 /m^2 different tillers were present during the second growing season; there were 344.6 /m^2 more total tillers than during the first growing season. During mid season, 375.9 /m^2 lead tillers developed into reproductive flowering stages (29.3% of the tiller population). Before reaching maturity, 438.6 /m^2 vegetative tillers terminated. Between mid August and mid October, 188.0 /m^2 fall tillers developed. During mid October, 657.8 /m^2 live vegetative tillers remained, of which, 250.6 /m^2 were lead tillers, 219.3 /m^2 were secondary tillers, and 188.0 /m^2 were fall tillers; there were 62.7 /m^2 more live vegetative tillers than during mid October of the first growing season.

Mid June 25% Treatment

The first year on the mid June 25% defoliation treatment of the traditional seasonlong management strategy (table 15, figure 5) started in early May with 438.6 /m^2 vegetative tillers including 250.6 /m^2 lead tillers and 188.0 /m^2 secondary tillers. Assuming the lead tillers were carry over tillers from the previous growing season. Vegetative reproduction produced 31.3 /m^2 tillers during the first growing season with 0.0 /m^2 initiated during May and 31.3 /m^2 initiated during mid season. A total of 469.9 /m^2 different tillers were present during the first growing season. During mid season, 94.0 /m^2 lead tillers developed into reproductive flowering stages (20.0% of the tiller population). Before reaching maturity, 156.6 /m^2 vegetative tillers terminated. Between mid August and mid October, 125.3 /m^2 fall tillers developed. During mid October, 344.6 /m^2 live vegetative tillers remained, of which, 62.7 /m^2 were lead tillers, 156.6 /m^2 were secondary tillers, and 125.3 /m^2 were fall tillers. During the winter period, 0.0 /m^2 tillers terminated. The second year on the mid June 25% defoliation treatment (table 15, figure 5) started in early May with 344.6 /m^2 vegetative tillers including 219.3 /m^2 lead tillers and 125.3 /m^2 secondary tillers, of which, 344.6 /m^2 were carry over tillers and 0.0 /m^2 were early spring initiated tillers; there were 94.0 /m^2 fewer tillers than during May of the first growing season. Vegetative reproduction produced 188.0 /m^2 tillers during the second growing season with 62.7 /m^2 initiated during May and 125.3 /m^2 initiated during mid season. A total of 532.5 /m^2 different tillers were present during the second growing season; there were 62.7 /m^2 more total tillers than during the first growing season. During mid season, 125.3 /m^2 lead tillers developed into reproductive flowering stages (23.5% of the tiller population). Before reaching maturity, 156.6 /m^2 vegetative tillers terminated. Between mid August and mid October, 125.3 /m^2 fall tillers developed. During mid October, 375.9 /m^2 live vegetative tillers remained, of which, 188.0 /m^2 were lead tillers, 62.7 /m^2 were secondary tillers, and 125.3 /m^2 were fall tillers; there were 31.3 /m^2 more live vegetative tillers than during mid October of the first growing season.

The first year on the mid June 25% defoliation treatment of the twice-over rotation management strategy (table 15, figure 5) started in early May with 971.1 /m^2 vegetative tillers including 595.2 /m^2 lead tillers and 375.9 /m^2 secondary tillers. Assuming the lead tillers were carry over tillers from the previous growing season. Vegetative reproduction produced 62.7 /m^2 tillers during the first growing season with 31.3 /m^2 initiated during May and 31.3 /m^2 initiated during mid season. A total of 1033.8 /m^2 different tillers were present during the first growing season. During mid season, 156.6 /m^2 lead tillers developed into reproductive flowering stages (15.1% of the tiller population). Before reaching maturity, 407.2 /m^2 vegetative tillers terminated. Between mid August and mid October, 344.6 /m^2 fall tillers developed. During mid October, 814.5 /m^2 live vegetative tillers remained, of which, 313.3 /m^2 were lead tillers, 156.6 /m^2 were secondary tillers, and 344.6 /m^2 were fall tillers. During the winter period, 188.0 /m^2 tillers terminated. The second year on the mid June 25% defoliation treatment (table 15, figure 5) started in early May with 1096.4 /m^2 vegetative tillers including 845.8 /m^2 lead tillers and 250.6 /m^2 secondary tillers, of which, 626.5 /m^2 were carry over tillers and 469.9 /m^2 were early spring initiated tillers; there were 125.3 /m^2 more tillers than during May of the first growing season. Vegetative reproduction produced 188.0 /m^2 tillers during the second growing season with 156.6 /m^2 initiated during May and 31.3 /m^2 initiated during mid season. A total of 1284.4 /m^2 different tillers were present during the second growing season; there were 250.6 /m^2 more total tillers than during the first growing season. During mid season, 188.0 /m^2 lead tillers developed into reproductive flowering stages (14.6% of the tiller population). Before reaching maturity, 281.9 /m^2 vegetative tillers terminated. Between mid August and mid October, 219.3 /m^2 fall tillers developed. During mid October, 1033.8 /m^2 live vegetative tillers remained, of which, 657.8 /m^2 were lead tillers, 156.6 /m^2 were secondary tillers, and 219.3 /m^2 were fall tillers; there were 219.3 /m^2 more live vegetative tillers than during mid October of the first growing season.

The mid June 25% treatment of the seasonlong management strategy had 55.6% greater pregrazed tiller density during the first May, 63.8% greater mean monthly tiller density during the first growing season, 15.4% lower pregrazed tiller density during the second May, and the same mean monthly tiller density during the second grazing season than that on the control treatment of the seasonlong management strategy (table 16, figure 5). The mid June 25% treatment of the twice-over management strategy had 10.7% greater pregrazed tiller density during the first May, 1.3% greater mean monthly tiller density during the first grazing season, 6.1% greater pregrazed tiller density during the second May, and 25.1% greater mean monthly tiller density during the second grazing season than that on the control treatment of the twice-over management strategy (table 16, figure 5).

The control treatment of the twice-over management strategy had 211.1% greater pregrazed tiller density during the first May, 231.9% greater mean monthly tiller density the first grazing season, 153.9% greater pregrazed tiller density during the second May, and 128.0% greater mean monthly tiller density during the second grazing season than that on the control treatment of the seasonlong management strategy (table 16, figure 5). The mid June 25% treatment of the twice-over management strategy had 121.4% greater pregrazed tiller density during the first May, 105.2% greater mean monthly tiller density during the first grazing season, 218.2% greater pregrazed tiller density during the second May, and 185.3% greater mean monthly tiller density during the second grazing season than that on the mid June 25% treatment of the seasonlong management strategy (table 16, figure 5).

Tiller Initiation

Control Treatment

A total of 657.9/m^2 secondary tillers were initiated by vegetative reproduction from axillary buds on the control treatment of the traditional seasonlong management strategy with 47.6% occurring during the spring, 14.3% occurring during the summer, and 38.1% occurring during the fall periods (table 17).

A total of 1472.3/m^2 secondary tillers were initiated by vegetative reproduction from axillary buds on the control treatment of the twice-over management strategy with 59.6% occurring during the spring, 10.6% occurring during the summer, and 29.8% occurring during the fall periods (table 17).

Mid June 25% Treatment

A total of 657.9/m^2 secondary tillers were initiated by vegetative reproduction from axillary buds on the mid June 25% defoliation treatment of the traditional seasonlong management strategy with 38.1% occurring during the spring, 23.8% occurring during the summer, and 38.1% occurring during the fall periods (table 17).

A total of 1660.4/m^2 secondary tillers were initiated by vegetative reproduction from axillary buds on the mid June 25% defoliation treatment of the twice-over management strategy with 62.3% occurring during the spring, 3.8% occurring during the summer, and 34.0% occurring during the fall periods (table 17).

The initiation of vegetative tillers during spring before grazing started appear to be more affected by the management and conditions of the previous growing season than to those of the current growing season. The initiation of vegetative tillers during the mid summer period had the lowest tiller numbers on all treatments of all management strategies because this period occurred simultaneously with the high resource demand period in which the dominant reproductive lead tillers progressed through the flower stages and produced seeds with low resources available for secondary tiller development. The cool season grass fall tiller initiation period, mid August to mid October, started after the lead tillers had completed most of their active growth and occurred simultaneously with the winter hardening process of perennial grasses.

The mid June 25% treatment of the seasonlong management strategy had 20% lower spring initiated tiller density, 66.6% greater summer initiated tiller density, and the same fall initiated tiller density resulting in the same total initiated vegetative tiller density than that on the control treatment of the seasonlong management strategy (table 17). The mid June 25% treatment of the twice-over management strategy had 17.9% greater spring initiated tiller density, 60.0% lower summer initiated tiller density, and 28.6% greater fall initiated tiller density resulting in 12.8% greater total initiated vegetative tiller density than that on the control treatment of the twice-over management strategy (table 17).

The control treatment of the twice-over management strategy had 180.0% greater spring initiated tiller density, 66.6% greater summer initiated tiller density, and 75.0% greater fall initiated tiller density resulting in 123.8% greater total initiated vegetative tiller density than that on the control treatment of the seasonlong management strategy (table 17). The mid June 25% treatment of the twice-over management strategy had 312.5% greater spring initiated tiller density, 60.0% lower summer initiated tiller density, and 125.0% greater fall initiated tiller density resulting in 152.4% greater total initiated vegetative tiller density than that on the mid June 25% treatment of the seasonlong management strategy (table 17). It is important to note that during the biweekly measurements of huge numbers of tillers during two growing seasons no seedlings were encountered on any treatment of all the management strategies.

Development of vegetative secondary tillers from axillary buds is regulated by a growth inhibiting hormone, auxin, produced in the apical meristem and young developing leaves of lead tillers (Briske and Richards 1995). Auxin interferes with the performance of a growth hormone, cytokinin, preventing tiller growth from axillary buds. Partial defoliation that removes 25% to 33% of the leaf area of lead tillers at vegetative phenological growth between the three and a half new leaf stage and the flower stage reduces the quantity of lead tiller auxin permitting cytokinin to stimulate metabolic activity in the axillary buds. Secondary tiller growth and development from axillary buds also requires the availability of sufficient carbohydrates and essential elements. If these requirements are available, tiller initiation occurs soon after stimulation. However, if these requirements are not available, tiller initiation is delayed until sufficient nutrients become available. Some stimulated axillary buds may terminate at the end of the growing season from lack of adequate resources. Increasing grass tiller density in a grassland ecosystem requires management that intentionally stimulates axillary bud metabolic activity, retains 66% to 75% of the predefoliated tiller leaf area that can fix the required quantity of carbohydrates, and maintains a large enough rhizosphere microbial biomass to mineralize adequate amounts of essential elements.

Tiller Termination

Control Treatment

A total of 375.9/m^2 tillers terminated on the control treatment of the seasonlong management strategy (table 18), of which 250.6/m^2 were vegetative tillers terminated prematurely with 0.0% terminating during spring and 100.0% terminating during the grazing period, 125.3/m^2 were lead tillers terminated after flowering, and no tillers terminated during the winter period. A total of 469.9/m^2 remained alive resulting in a 44.4% termination rate.

A total of 1440.9/m^2 tillers terminated on the control treatment of the twice-over management strategy (table 18), of which 689.1/m^2 were vegetative tillers terminated prematurely with 40.9% terminating during spring and 59.1% terminated during the grazing period, 720.5/m^2 were lead tillers terminated after flowering, and 31.3/m^2 tillers terminated during the winter period. A total of 657.7/m^2 tillers remained alive resulting in a 68.7% termination rate.

Mid June 25% Treatment

A total of 532.6/m^2 tillers terminated on the mid June 25% defoliation treatment of the seasonlong management strategy (table 18), of which 313.3/m^2 were vegetative tillers terminated prematurely with 0.0% terminating during spring and 100.0% terminating during the grazing period, 219.3/m^2 were lead tillers terminated after flowering, and no tillers terminated during the winter period. A total of 375.9/m^2 tillers remained alive resulting in a 58.6% termination rate.

A total of 1221.8/m^2 tillers terminated on the mid June 25% defoliation treatment of the twice-over management strategy (table 18), of which 689.2/m^2 were vegetative tillers terminated prematurely with 18.2% terminating during spring and 81.8% terminating during the grazing period, 344.6/m^2 were lead tillers terminated after flowering, and 188.0/m^2 tillers terminated during the winter period. A total of 1033.8/m^2 tillers remained alive resulting in a 54.2% termination rate.

Winter survival and spring regrowth of carryover tillers depend on having adequate carbohydrate reserves. The quantity of carbohydrates stored during the winter hardening process is closely related to the amount of active leaf material on each tiller. Tillers with abundant leaf area during late summer and early fall can store adequate quantities of carbohydrates to survive the winter and produce robust leaves the following spring. Winter dormancy in perennial grasses is not total inactivity, but reduced activity. The crown, portions of the root system, and some leaf tissue remain at low activity and maintain physiological processes throughout the winter by using stored carbohydrates. Cool season grasses continue leaf growth at slow rates during winter. Some tillers with low carbohydrates reserves do not survive until spring. The rate at which plants respire, or use, stored carbohydrates during winter is affected by the amount of insulation standing plant material and snow provide from the cold winter air temperatures. The greater the amount of insulation, the more slowly the plant draws on its carbohydrate reserves. With low amounts of insulation, very rapid respiration can occur and deplete carbohydrate reserves before spring, causing tiller death called “winter kill”.

The carryover tillers that survive to spring depend on the low amounts of remaining carbohydrate reserves and on the photosynthetic products produced from the portions of previous years leaves that overwintered without cell wall rupture and regreened with chlorophyll. A little later in the spring dependence on photosynthetic product produced by new young leaves increases. The low quantity of reserve carbohydrates and photosynthetic product from carryover leaves may not be adequate to supply the entire amount required to support root growth and also support new leaf growth causing either a great reduction in active growth or a stoppage of growth resulting in spring tiller termination.

During the grazing period, secondary vegetative tillers are totally dependent on a lead tiller for access to carbohydrates and mineral nitrogen during early leaf stages through the 3 leaf stage and maybe for most of the 4 leaf stage. These subordinate secondary tiller have slow and inhibited growth development with some secondary tillers remaining at the 2 and 3 leaf stage for most of the growing season. During periods when the lead tiller is experiencing high resource demand, such as, progressing through the flower stages or post partial defoliation processes to accelerate replacement leaf and shoot growth and increasing photosynthetic capacity of remaining mature leaves diverts nutrient resources away from secondary tillers at levels that may result in tiller termination.

The mid June 25% treatment of the seasonlong management strategy had the same low spring terminated tiller density, 25.0% greater grazing period terminated tiller density, 75.0% greater terminated flowering tiller density, and the same low winter terminated tiller density resulting in 41.7% greater total terminated tiller density than that on the control treatment of the seasonlong management strategy (table 18). The mid June 25% treatment of the twice-over management strategy had 55.6% lower spring terminated tiller density, 38.5% greater grazing period terminated tiller density, 52.2% lower terminated flowering tiller density, and 500.0% greater winter terminated tiller density resulting in 15.2% lower total terminated tiller density than that on the control treatment of the twice-over management strategy (table 18).

The control treatment of the twice-over management strategy had 100.0% greater spring terminated tiller density, 62.5% greater grazing period terminated tiller density, 475.0% greater terminated flowering tiller density, and 100.0% greater winter terminated tiller density resulting in 283.3% greater total terminated tiller density than that on the control treatment of the seasonlong management strategy (table 18). The mid June 25% treatment of the twice-over management strategy had 100.0% greater spring terminated tiller density, 80.0% greater grazing period terminated tiller density, 57.1% greater terminated flowering tiller density, and 100.0% greater winter terminated tiller density resulting in 129.4% greater total terminated tiller density than that on the mid June 25% treatment of the seasonlong management strategy (table 18).

Tiller Type Rate of Growth

The tiller types were classified as reproductive lead tillers, vegetative lead tillers, and secondary vegetative tillers. Rates of tiller growth and development were regulated by hormones and availability of essential elements. The dominant tillers with rapid or unimpeded growth were the reproductive lead tillers and then the vegetative lead tillers. The subordinate tillers with slow or inhibited growth were the secondary tillers.

Almost all grass tillers grow and develop during two growing seasons. Reproductive lead tillers are derived from carryover tillers that were vegetative lead tillers during the previous growing season and following development of sexual reproductive seed stalks, these reproductive lead tillers will terminate at the end of the growing season. Vegetative lead tillers are derived from carryover tillers that were cool season fall tillers or late season developed vegetative tillers of the previous growing season and from spring initiated tillers that were stimulated during the previous growing season. These vegetative lead tillers can produce 6 to 10 leaves during the growing season depending on when they became independent tillers. Most of these vegetative lead tillers will carryover and become the reproductive lead tillers of the next growing season. Secondary vegetative tillers are derived from current season stimulated and initiated spring and summer tillers that remain dependent on a lead tiller until the 3.5 new leaf or 4 leaf stage. These secondary tillers can produce 6 to 8 leaves during the growing season depending on when they become independent tillers. The quantity of carbohydrates that these secondary tillers are able to store during the winter hardening period, mid August to mid October, determines their future development. Most of the secondary tillers will carryover and become the vegetative lead tillers of the next growing season, with a few robust secondary tillers becoming reproductive lead tillers. Some of the secondary tillers with few functional leaves will be able to store only low levels of carbohydrates and will terminate during the winter.

All of the vegetative tillers that did not produce a seed head move into winter as living tillers even though their green chlorophyll has faded and they appear similar in color to the tan of terminated reproductive lead tillers. The green colored leaves that appear soon after the snow melts are not new leaves, they are carryover last years leaves with cell walls that did not rupture. The new leaf growth of the carryover tillers will depend on the quantity of carryover leaf area that regreens early that next spring. Removal of the carryover leaves during late season and winter grazing greatly reduces the density of surviving tillers and the quantity of new leaf production.

The reproductive lead tillers had the fastest rate of growth and development. Usually 5 to 8 leaves had developed when reproductive lead tillers reached the flower (anthesis) stage and no additional leaves were produced during development of flower stalk stages. Reproductive lead tillers that produced flower stalks early in the flower period had 5 to 6 leaves and tillers that produced flower stalks late in the flower period had 7 or 8 leaves. The period with the greatest rate of flower stalk development occurred between early June and mid July. The rate of leaf development of the reproductive tillers was not different among the defoliation treatments of the grazing management strategies. The flower period started at the same time on all defoliation treatments of every grazing management strategy. First flowers (anthesis) appeared during early June, before 21 June, the summer solstice, the day with the longest daylight of nearly 16 hours. However, the length of the flower period differed among the grazing management strategies. The end of the flower period occurred in early July on the control and mid June 25% treatments of the seasonlong management strategy and in mid July on the mid June 25% treatment and in early August on the control treatment of the twice-over management strategy. The low quantity of available mineral nitrogen of less than 100 lbs/ac (112 kg/ha) contributed to the shorter flowering periods on the traditional seasonlong management strategy. The quantity of available mineral nitrogen at greater than 100 lbs/ac contributed to the longer flowering periods on the treatments of the twice-over management strategy.

The vegetative lead tillers had the second fastest rate of growth and development. The vegetative lead tillers developed 3.6 leaves in 3 months from the 3.0 leaf stage in early May to the 6.6 leaf stage in early August. The vegetative lead tillers were at the 4.0 leaf stage during early June. The period with the greatest rate of leaf development occurred between early June and early July. The greatest rate of leaf development occurred on the mid June 25% treatment of the twice-over management strategy. The lowest rate of leaf development occurred on the control treatment of the seasonlong management strategy. The rate of leaf stage development was not different among the reproductive lead tillers that had not produced flower stalks and the vegetative lead tillers on the same treatments of the grazing management strategies.

The secondary tillers that survive to the end of the growing season were subordinate to a lead tiller and had very slow rates of growth and development. Secondary tillers developed at an average rate of 0.4 leaves per month. During early July, secondary tillers were at the 3.0 leaf stage on the seasonlong management strategy and at the 3.5 leaf stage on the twice-over management strategy. Secondary tillers were totally dependent on a lead tiller for access to carbohydrates and mineral nitrogen during early leaf stages through the 3.0 leaf stage and had very slow rates of leaf development. After the reproductive lead tillers had completed the greatest amount of leaf development around mid July, several of the secondary tillers developed additional leaves at faster rates. With the full development of leaf 3 and some of leaf 4, secondary tillers seemed to transition into being independent.

Most of the growth in tillers leaf height and most of the development in tiller leaf stage by the reproductive and vegetative lead tillers occurred during May, June, and July. Goetz (1963) found that lead tillers completed 100% of the growth in tiller leaf height and cool season grass flower stalk height by the end of July. In warm season grasses, a small amount of flower stalk elongation occurs after late July (Manske 2000c). This rapid growth period corresponds with the period of greatest precipitation. The precipitation received during May, June, and July accounts for more than 50% of the annual precipitation of the Northern Mixed Grass Prairie (Manske et al. 2010d).

Tiller Type Density

Control Treatment

A total mean monthly tiller density of 342.0/m^2 was present on the control treatment of the traditional seasonlong management strategy (table 19), with 62.7/m^2 reproductive lead tillers, 146.2/m^2 vegetative lead tillers, and 133.1/m^2 secondary vegetative tillers.

A total mean monthly tiller density of 898.0/m^2 was present on the control treatment of the twice-over management strategy (table 19), with 352.5/m^2 reproductive lead tillers, 266.3/m^2 vegetative lead tillers, and 279.3/m^2 secondary vegetative tillers.

Mid June 25% Treatment

A total mean monthly tiller density of 415.1/m^2 was present on the mid June 25% treatment of the traditional seasonlong management strategy (table 19), with 99.2/m^2 reproductive lead tillers, 159.2/m^2 vegetative lead tillers, and 156.6/m^2 secondary vegetative tillers.

A total mean monthly tiller density of 1049.4/m^2 was present on the mid June 25% treatment of the twice-over management strategy (table 19), with 172.3/m^2 reproductive lead tillers, 543.0/m^2 vegetative lead tillers, and 334.2/m^2 secondary vegetative tillers.

The mid June 25% treatment of the seasonlong management strategy (table 19) had 21.4% more total tiller types, with 58.2% more reproductive lead tiller types, 8.9% more vegetative lead tiller types, and 17.7% more secondary tiller types than that on the control treatment of the seasonlong management strategy. The mid June 25% treatment of the twice-over management strategy (table 19) had 16.9% more total tiller types, with 51.1% less reproductive lead tiller types, 103.9% more vegetative lead tiller types, and 19.7% more secondary tiller types than that on the control treatment of the twice-over management strategy.

The control treatment of the twice-over management strategy (table 19) had 162.6% more total tiller types, with 462.2% more reproductive lead tiller types, 82.1% more vegetative lead tiller types, and 109.8% more secondary tiller types than that on the control treatment of the seasonlong management strategy. The mid June 25% treatment of the twice-over management strategy (table 19) had 152.8% more total tiller types, with 73.7% more reproductive lead tiller types, 241.1% more vegetative lead tiller types, and 113.4% more secondary tiller types than that on the mid June 25% treatment of the seasonlong management strategy.

Forage Tillers

Not all grass tillers present on a grassland ecosystem are forage tillers. Forage tillers are that portion of grass tillers that provide nourishment for livestock. The grass tillers that do not have sufficient quantity of leaf stage development or quality of nutrients are not forage tillers. Reproductive lead tillers derived from carryover tillers are forage tillers when between the 4 leaf stage and flower stage. Vegetative lead tillers derived from carryover tillers or from early spring initiated tillers are forage tillers when between the 4 leaf and 10 leaf stages. Secondary tillers derived from growing season initiated tillers are forage tillers after they develop the 4 leaf stage until the 8 leaf stage. The number of forage tillers produced during a growing season are greatly affected by the grazing management strategy.

Control Treatment

Forage tillers on the control treatment of the seasonlong management strategy were comprised of 18% reproductive lead tillers which are derived from carryover tillers. The density of reproductive lead tillers between the 4 leaf stage and the flower stage increased from 15.6/m^2 in early May to 47.0/m^2 at start of grazing in early June as tillers developed additional leaves, then decreased to 15.6/m^2 in early July and 0.0/m^2 in mid July as lead tillers reached the flower stage (table 20, figure 6). Forage tillers were comprised of 43% vegetative lead tillers which are derived from carryover tillers and spring initiated tillers. The density of vegetative lead tillers between the 4 leaf stage and the 10 leaf stage increased from 15.6/m^2 in early May to 78.3/m^2 at start of grazing in early June, continued increasing to 156.6/m^2 in early July and remained at 156.6/m^2 until end of grazing in mid October (table 20, figure 6). Forage tillers were comprised of 39% secondary tillers which are derived from growing season initiated tillers. The density of secondary tillers between the 4 leaf stage and the 8 leaf stage remained at 0.0/m^2 from early May through early June, then increased to 15.6/m^2 in mid June, increased to 31.3/m^2 in mid July, decreased to 15.6/m^2 in early August, and increased to 47.0/m^2 in late August, and to 78.3/m^2 at end of grazing in mid October (table 20, figure 6). Density of mean total tillers was 341.5/m^2 during the grazing season. The density of total forage tillers between the 4 leaf stage and the flower stage or the 10 leaf stage started at 31.3/m^2 in early May, increased to 125.3/m^2 at start of grazing in early June, increased to 188.0/m^2 in early and mid July decreased to 172.3/m^2 in early August, increased to 203.6/m^2 in late August, and peaked at 235.0/m^2 at end of grazing in mid October (table 20, figure 6).

Forage tillers on the control treatment of the twice-over management strategy were comprised of 39% reproductive lead tillers which are derived from carryover tillers. The density of reproductive lead tillers between the 4 leaf stage and the flower stage increased from 125.3/m^2 in early May to 281.9/m^2 at start of grazing in early June as tillers developed additional leaves, then decreased to 156.6/m^2 in early July, to 31.3/m^2 in early August, and then to 0.0/m^2 as lead tillers reached the flower stage (table 20, figure 6). Forage tillers were comprised of 30% vegetative lead tillers which are derived from carryover tillers and spring initiated tillers. The density of vegetative lead tillers between the 4 leaf stage and the 10 leaf stage increased from 47.0/m^2 in early May to 188.0/m^2 at start of grazing in early June, continued increasing and peaked at 266.3/m^2 during early and mid July, then decreased to 235.0/m^2 in early August and remained at that level until end of grazing in mid October (table 20, figure 6). Forage tillers were comprised of 31% secondary tillers which are derived from growing season initiated tillers. The density of secondary tillers between the 4 leaf stage and the 8 leaf stage started at 31.3/m^2 in early May, increased to 78.3/m^2 at start of grazing in early June, continued to increase at 109.6/m^2 in early July and peaked at 172.3/m^2 in early August, then decreased to 156.6/m^2 at end of grazing in mid October (table 20, figure 6). Density of mean total tillers was 883.4/m^2 during the grazing season. The density of total forage tillers between the 4 leaf stage and the flower stage or the 10 leaf stage started at 203.6/m^2 in early May, increased to 548.2/m^2 at start of grazing in early June, peaked at 595.2/m^2 in mid June, then decreased to 532.5/m^2 in early July, to 438.6/m^2 in early August, and to 391.6/m^2 at end of grazing in mid October (table 20, figure 6).

Mid June 25% Treatment

Forage tillers on the mid June 25% treatment of the seasonlong management strategy were comprised of 24% reproductive lead tillers which are derived from carryover tillers. The density of reproductive lead tillers between the 4 leaf stage and the flower stage increased from 15.6/m^2 in early May to a peak of 62.7/m^2 at start of grazing in early June as tillers developed additional leaves, then decreased to 47.0/m^2 in mid June, to 31.3/m^2 in early July, and to 0.0/m^2 in mid July as lead tillers reached the flower stage (table 20, figure 6). Forage tillers were comprised of 38% vegetative lead tillers which are derived from carryover tillers and spring initiated tillers. The density of vegetative lead tillers between the 4 leaf stage and the 10 leaf stage increased from 47.0/m^2 in early May to 141.0/m^2 at start of grazing in early June, then peaked at 156.6/m^2 in mid June remaining at that level until early August, and decreased to 125.3/m^2 at end of grazing in mid October (table 20, figure 6). Forage tillers were comprised of 38% secondary tillers which are derived from growing season initiated tillers. The density of secondary tillers between the 4 leaf stage and the 8 leaf stage remained a 0.0/m^2 from early May through mid June, increased to 31.3/m^2 in early July until early August, peaked at 109.6/m^2 in late August, and decreased to 94.0/m^2 at end of grazing in mid October (table 20, figure 6). Density of mean total tillers was 429.2/m^2 during the grazing season. The density of total forage tillers between the 4 leaf stage and the flower stage or the 10 leaf stage started at 62.7/m^2 in early May, increased to 203.6/m^2 at start of grazing in early June to mid June, increased to 219.3/m^2 in early July, decreased to 188.0/m^2 during mid July to early August, then peaked at 234.9/m^2 in late August, and decreased to 219.3/m^2 at end of grazing in mid October (table 20, figure 6).

Forage tillers on the mid June 25% treatment of the twice-over management strategy were comprised of 16% reproductive lead tillers which are derived from carryover tillers. The density of reproductive lead tillers between the 4 leaf stage and the flower stage increased from 78.3/m^2 in early May and peaked at 172.3/m^2 at start of grazing in early June as tillers developed additional leaves, then decreased to 141.0/m^2 in mid June, to 62.7/m^2 in early July, to 15.6/m^2 in mid July, and to 0.0/m^2 in early August as lead tillers reached the flower stage (table 20, figure 6). Forage tillers were comprised of 52% vegetative lead tillers which are derived from carryover tillers and spring initiated tillers. The density of vegetative lead tillers between the 4 leaf stage and the 10 leaf stage increased from 188.0/m^2 in early May, to 532.5/m^2 at start of grazing in early June, then peaked at 579.5/m^2 in mid June, decreased to 516.9/m^2 in early July until early August, then decreased to 485.6/m^2 in late August until end of grazing in mid October (table 20, figure 6). Forage tillers were comprised of 32% secondary tillers which are derived from growing season initiated tillers. The density of secondary tillers between the 4 leaf stage and the 8 leaf stage started at 15.6/m^2 in early May, reached the level of 15.6/m^2 again at start of grazing in early June, increased to a first peak of 203.6/m^2 in early July, decreased gradually to 141.0/m^2 in early August until late August, and then increased to a second peak of 203.6/m^2 at end of grazing in mid October (table 20, figure 6). Density of mean total tillers was 1030.7/m^2 during the grazing season. The density of total forage tillers between the 4 leaf stage and the flower stage or the 10 leaf stage started at 281.9/m^2 in early May, increased to 720.5/m^2 at start of grazing in early June, continued to increase to peak of 783.2/m^2 in early July, then gradually decreased to 689.2/m^2 in mid July, to 657.8/m^2 in early August, to 626.6/m^2 in late August, and increased to 689.2/m^2 at end of grazing in mid October (table 20, figure 6).

The primary period the reproductive lead tillers were forage tillers was from early June until mid July while at phenological growth stages between the 4 leaf stage and the flower stage. The primary period the vegetative lead tillers were forage tillers was from early June until mid October while at phenological growth stages between the 4 leaf stage and 10 leaf stage. The primary period the secondary tillers were forage tillers was from early July until mid October while at phenological growth stages between the 4 leaf stage and 8 leaf stage. The forage tillers are comprised primarily of preflower reproductive lead tillers and vegetative lead tillers during the first grazing period from early June to mid July. During the second grazing period from mid July to mid October, the forage tillers are comprised primarily of vegetative lead tillers and secondary tillers.

Forage tiller density on the control treatment of the seasonlong management strategy was 160.6/m^2 (45.6%) during the early June to mid July grazing period and was 199.7/m^2 (59.8%) during the mid July to mid October grazing period. Forage tiller density on the mid June 25% treatment of the seasonlong management strategy was 203.6/m^2 (48.1%) during the early June to mid July grazing period and was 207.6/m^2 (47.9%) during the mid July to mid October grazing period. The beneficial affects from the mid June 25% treatment on forage tiller density was a 26.8% increase during the early June to mid July grazing period and was a 4.0% increase during the mid July to mid October grazing period with a total forage tiller density of 208.1/m^2 (48.5%) during the early June to mid October grazing period that was 16.3% greater than the total forage tiller density of 179.0/m^2 (52.4%) on the control treatment of the seasonlong management strategy (table 21).

Forage tiller density on the control treatment of the twice-over management strategy was 532.5/m^2 (60.2%) during the early June to mid July grazing period and was 411.2/m^2 (46.6%) during the mid July to mid October grazing period. Forage tiller density on the mid June 25% treatment of the twice-over management strategy was 740.1/m^2 (68.5%) during the early June to mid July grazing period and was 665.7/m^2 (66.8%) during the mid July to mid October grazing period. The beneficial affects from the mid June 25% treatment on forage tiller density was a 39.0% increase during the early June to mid July grazing period and was a 61.9% increase during the mid July to mid October grazing period with a total forage tiller density of 704.9/m^2 (68.4%) during the early June to mid October grazing period that was 48.6% greater than the total forage tiller density of

474.4/m^2 (53.7%) on the control treatment of the twice-over management strategy (table 21).

The control treatment of the twice-over management strategy had a 165.0% greater forage tiller density during the early June to mid October grazing period with 231.6% greater forage tiller density during the early June to mid July grazing period and 105.9% greater forage tiller density during the mid July to mid October grazing period than that on the control treatment of the seasonlong management strategy (table 21). The mid June 25% treatment of the twice-over management strategy had a 238.7% greater forage tiller density during the early June to mid October grazing period with 263.5% greater forage tiller density during the early June to mid July grazing period and 220.7% greater forage tiller density during the mid July to mid October grazing period than that on the mid June 25% treatment of the seasonlong management strategy (table 21).

The not forage tiller density on the control treatment of the seasonlong management strategy was 191.9/m^2 (54.4%) during the early June to mid July grazing period and was 134.5/m^2 (40.2%) during the mid July to mid October grazing period. The not forage tiller density on the mid June 25% treatment of the seasonlong management strategy was 219.3/m^2 (51.9%) during the early June to mid July grazing period and was 225.7/m^2 (52.1%) during the mid July to mid October grazing period. The beneficial affects from the mid June 25% treatment on the not forage tiller density was a 14.3% increase during the early June to mid July grazing period and was a 67.8% increase during the mid July to mid October grazing period with a total not forage tiller density of 221.1/m^2 (51.5%) during the early June to mid October grazing period that was 36.1% greater than the total not forage tiller density of 162.5/m^2 (47.6%) on the control treatment of the seasonlong management strategy (table 21).

The not forage tiller density on the control treatment of the twice-over management strategy was 352.5/m^2 (39.8%) during the early June to mid July grazing period and was 471.2/m^2 (53.4%) during the mid July to mid October grazing period. The not forage tiller density on the mid June 25% treatment of the twice-over management strategy was 340.7/m^2 (31.5%) during the early June to mid July grazing period and was 331.5/m^2 (33.2%) during the mid July to mid October grazing period. The beneficial affects from the mid June 25% treatment on the not forage tiller density was a 3.3% decrease during the early June to mid July grazing period and was a 29.6% decrease during the mid July to mid October grazing period with a total not forage tiller density of 325.8/m^2 (31.6%) during the early June to mid October grazing period that was a 20.3% decrease from the total not forage tiller density of 409.0/m^2 (46.3%) on the control treatment of the twice-over management strategy (table 21).

The control treatment of the twice-over management strategy had 151.7% greater not forage tiller density during the early June to mid October grazing period with 83.7% greater not forage tiller density during the early June to mid July grazing period and 250.3% greater not forage tiller density during the mid July to mid October grazing period than that on the control treatment of the seasonlong management strategy (table 21). The mid June 25% treatment of the twice-over management strategy had a 47.4% greater not forage tiller density during the early June to mid October grazing period with 55.4% greater not forage tiller density during the early June to mid July grazing period and 46.9% greater not forage tiller density during the mid July to mid October grazing period than that on the mid June 25% treatment of the seasonlong management strategy (table 21).

During the total early June to mid October grazing period there was a 10.2% greater forage tiller density than not forage tiller density on the control treatment and there was a 6.2% greater not forage tiller density than forage tiller density on the mid June 25% treatment of the seasonlong management strategy (table 21).

During the total early June to mid October grazing period there was a 16.0% greater forage tiller density than not forage tiller density on the control treatment and there was a 116.34% greater forage tiller density than not forage tiller density on the mid June 25% treatment of the twice-over management strategy (table 21).

The difference between the tiller densities of the forage tillers and the not forage tillers was not very much on the control and mid June 25% treatments of the seasonlong management strategy and on the control treatemnt of the twice-over management strategy, however, the difference between the tiller densities of the forage tillers and the not forage tillers was huge on the mid June 25% treatment of the twice-over management strategy (table 21).

Tillers that remain vegetative and carryover into the following growing season are able to continue production of leaf primordia becoming that growing seasons lead tillers. While reproductive lead tillers are at vegetative stages between the 3 leaf stage and 3.5 leaf stage, the apical meristem ceases producing leaf primordia and commences producing flower primordia (Frank 1996, Frank et al. 1997). At the 3.5 leaf stage, all of the leaf primordia that will develop into leaves during the second growing season have been produced on the apical meristem of reproductive lead tillers. All previously produced leaf primordia continue to grow and develop. The flower stalk development can eventually be observed externally at the boot stage. Reproductive lead tillers terminate new leaf growth and development with the emergence of the flower stalk and elongation of 4 or 5 of the upper internodes with the attached leaf sheaths. As the flower stalk develops, the fiber content increases and the percent crude protein, percent water, and digestibility decrease. Shortly after the flower (anthesis) stage, crude protein levels drop below 9.6%, the minimum requirements for lactating cows (NRC 1996). Between the flower stage and the seed mature stage, crude protein levels decrease rapidly and drop below 7.8% by early August and drop below 6.2% in late August (Whitman et al. 1951, Manske 2008b). Reproductive lead tillers at phenological stages advanced of the flower stage yield minuscule quantities of forage because the crude protein content is below the nutrient requirements of lactating beef cattle.

Vegetative lead tillers and secondary tillers at leaf stages earlier than the 3.5 leaf stage had insufficient new leaf area without the additional photosynthetic leaf area from the carryover leaves to meet the required amounts of photosynthetic product for normal leaf growth and development. These early leaf stage tillers are not physiologically ready for partial defoliation and are not forage tillers until after they reach the 3.5 new leaf stage.

Vegetative lead tillers between the 4 leaf stage and the 6 or 8 leaf stage and sometimes to the 10 leaf stage, and secondary tillers between the 4 leaf stage and the 6 leaf stage and sometimes to the 8 leaf stage provide the primary source of forage tillers with crude protein quality at or above the nutrient requirements of lactating beef cows. The density of forage tillers between the 4 leaf stage and the 6 to 10 leaf stage directly affects the quantity of herbage biomass and the level of available crude protein. The quantity of crude protein captured per acre is directly related to the quantity of pounds of calf weight produced per acre and inversely related to the cost per pound of calf weight produced (Manske 2008d).

The substantially lower tiller densities on the traditional seasonlong management strategy were the result of a very low rhizosphere volume of only 1552.3 cm^3/m^3 with a low microbial biomass able to mineralize 85.9 kg/ha (76.7 lbs/ac) of mineral nitrogen which is below the threshold quantity of 112 kg/ha (100 lbs/ac). Partially defoliated tillers were unable to replace the quantity of leaf area removed and could only support the growth and development of a few secondary vegetative tillers from axillary buds at a density of 657.9/m^2. The native cool and warm season grasses on the seasonlong management strategy produced a mean monthly herbage biomass of 769.96 lbs/ac that had one peak at 850.55 lbs/ac in July (table 22, figure 7). Traditionally managed strategies usually are deficient of adequate quantity and quality of grass biomass during late season from mid July to mid October. The seasonlong management strategy had a native grass mean biomass of 785.89 lbs/ac (table 22, figure 7) during the second grazing period with a tiller density of 433.3/m^2 of which 47.9% were forage tillers (table 21) and most of the vegetative tillers with crude protein and phosphorus content below the requirements of lactating beef cows (tables 23 and 24, figures 8 and 9).

The biologically effective twice-over management strategy coordinated partial defoliation with grass phenological growth stages resulting in a large rhizosphere volume of 5212.9 cm^3/m^3 with a large microbial biomass able to mineralize 199.2 kg/ha (177.9 lbs/ac) of mineral nitrogen which is well above the threshold quantity of 112 kg/ha (100 lbs/ac). Partially defoliated tillers were able to replace the quantity of leaf area removed at a rate of 140% growth and were able to support the growth and development of initiated vegetative tillers from axillary buds at a density of 1660.4/m^2 (152.4% greater than that on the seasonlong management strategy). The native cool and warm season grasses on the twice-over management strategy produced a mean monthly herbage biomass of 1010.43 lbs/ac (31.2% greater than that on the seasonlong management strategy) that had one peak with lead tillers at 1064.94 lbs/ac in July and a greater second peak with vegetative tillers at 1127.75 lbs/ac in September (table 22, figure 7). Biologically effective management strategies usually have adequate quantity and quality of grass biomass during late season from mid July to mid October. The twice-over management strategy had native grass mean biomass of 1044.16 lbs/ac (32.9% greater than that on the seasonlong management strategy) (table 22, figure 7) during the second grazing period with a tiller density of 997.2/m^2 (130.1% greater than that on the seasonlong management strategy) of which 66.8% were forage tillers (table 21) and most of the vegetative and all of the secondary tillers with crude protein and phosphorus content above the requirements of lactating beef cows (tables 23 and 24, figures 8 and 9).

Grassland ecosystems managed by the biologically effective concept function at the biological potential levels. The ecosystem biogeochemical processes performed by the large volume rhizosphere with a large biomass of microbes mineralize large quantities of nitrogen and other essential elements. At the threshold quantity of 100 lbs/ac (112 kg/ha) available mineral nitrogen, the four primary internal plant growth mechanisms (compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency) perform at their greatest possible rates to help grass tillers withstand and fully recover from partial defoliation by grazing graminivores.

Discussion

Prairie ecosystems are more complex than the most complicated machines built by humans. Fortunately, grassland managers do not need to know how to build a prairie ecosystem to manage it properly. But, like the captain of a nuclear submarine or the pilot of a jumbo jet, grassland managers do need an understanding of how the major parts function in order to maintain everything working at potential level while they are in command. Unlike the captain or the pilot, who have access to a large technical work force, the grassland manager is often the entire technical crew. Most grassland managers identify themselves as livestock producers because thay have misinterpreted that their source of income originates from the sale of the livestock rather than from the land. The source of livestock weight is from renewable essential elements associated with the ecosystem that are recaptured by plants and soil microbes, recycled by soil microbes, and made available to the livestock through the renewed growth of forage grass plants. Grass plants require essential elements to grow. These critical ecosystem biogeochemical processes that mineralize essential elements do not work automatically and have not been included in traditional management concepts. This is the reason grassland ecosystems managed by traditional concepts produce around 50% of their potential, with a range from 30% to 70% of potential. The rhizosphere microbes perform the ecosystem biogeochemical processes (Manske 2015). The greater the biomass of rhizosphere microbes, the greater quantity of biogeochemical processes performed. The rhizosphere microbes are achlorophyllous and depend on grass plants for the source of short carbon chain energy. Grass plants can exudate short carbon chain energy into the rhizosphere during vegetative growth stages of lead tillers between the three and a half new leaf stage and the flower stage which happens each year between 1 June and 15 July following partial defoliation that removes 25% to 33% of the aboveground leaf biomass from 60% to 80% of the tillers by grazing graminivores. This partial defoliation also activates the grass plant growth mechanisms into functionality when 100 lbs/ac of mineral nitrogen is available. The compensatory physiological mechanisms give grass plants the capability to rapidly replace lost leaf and shoot biomass by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen. The vegetative reproduction by tillering mechanisms develops secondary tillers from growth of axillary buds. The nutrient resource uptake mechanisms enhance the competitiveness of nutrient and water resource uptake which maintains grass plant dominance within a grassland community. The water use efficiency mechanisms increases the quantity of herbage biomass produced per inch of precipitation received by 50.4%. These grass plant growth mechanisms must be activated by grazing graminivores but will not function unless 100 lbs/ac of mineral nitrogen is available through mineralization of organic nitrogen by rhizosphere microbes.

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Table 1. Growing season (May to August) herbage biomass (lbs/ac) by biotype categories on the sandy ecological site of the Biologically Effective management concept of years 1-2 and years 3-4, 1983-1986.

Sandy Years 1-2	May	Jun	Jul	Aug	Jun-Aug Mean
Cool Short	170.97	89.90	96.93	88.16	91.66
Cool Middle	268.80	334.75	400.21	342.14	359.03
Warm Tall	205.31	464.24	482.87	392.88	446.66
Warm Short	59.76	45.40	114.78	101.59	87.26
Upland Sedge	533.42	523.76	494.47	347.88	455.37
Forbs	82.66	140.94	197.03	211.30	183.09
Grasses	704.84	934.29	1094.79	924.77	984.61
Graminoids	1238.26	1458.05	1589.26	1272.65	1439.98
Total	1320.92	1598.99	1786.29	1483.95	1623.07

Years 3-4	May	Jun	Jul	Aug	Jun-Aug Mean
Cool Short	96.63	146.29	111.40	124.09	127.26
Cool Middle	321.76	440.06	462.06	449.57	450.56
Warm Tall	152.58	510.82	517.36	598.63	542.27
Warm Short	86.28	136.38	224.39	192.67	184.48
Upland Sedge	717.76	674.35	625.59	743.33	681.09
Forbs	107.04	123.30	160.16	163.73	149.06
Grasses	657.25	1233.55	1315.21	1364.96	1304.57
Graminoids	1375.01	1907.90	1940.80	2108.29	1985.66
Total	1482.05	2031.20	2100.96	2272.02	2134.72

Table 2. Growing season (May to August) herbage biomass (lbs/ac) by biotype categories on the shallow ecological site of the Biologically Effective management concept of years 1-2 and years 3-4, 1983-1986.

Shallow Years 1-2	May	Jun	Jul	Aug	Jun-Aug Mean
Cool Short	137.96	186.13	162.94	177.21	175.43
Cool Middle	125.92	261.16	220.33	340.05	273.85
Wheatgrass	8.03	40.29	28.10	24.98	31.12
Warm Short	124.88	132.81	140.94	160.07	144.61
Upland Sedge	235.34	218.54	137.07	165.02	173.54
Forbs	90.98	171.86	334.20	137.57	214.54
Grasses	396.79	620.39	552.31	702.31	625.01
Graminoids	632.13	838.93	689.38	867.33	798.55
Total	723.11	1010.79	1023.58	1004.90	1013.09

Years 3-4	May	Jun	Jul	Aug	Jun-Aug Mean
Cool Short	154.61	348.87	233.51	195.45	259.28
Cool Middle	220.97	292.78	401.20	374.64	356.21
Wheatgrass	10.70	59.47	13.08	39.25	37.27
Warm Short	125.83	330.84	413.89	403.59	382.77
Upland Sedge	227.86	230.53	244.61	162.94	212.69
Forbs	107.44	167.30	169.68	176.80	171.26
Grasses	512.11	1031.96	1061.68	1012.93	1035.53
Graminoids	739.97	1262.49	1306.29	1175.87	1248.22
Total	847.41	1429.79	1475.97	1352.67	1419.48

Table 3. Growing season (May to August) herbage biomass (lbs/ac) by biotype categories on the silty ecological site of the Biologically Effective management concept of years 1-2 and years 3-4, 1983-1986.

Silty Years 1-2	May	Jun	Jul	Aug	Jun-Aug Mean
Cool Short	95.74	120.42	154.91	223.99	166.44
Cool Middle	127.56	525.88	431.33	268.79	408.67
Wheatgrass	154.91	142.72	156.40	114.18	137.77
Warm Short	281.87	248.28	376.03	430.24	351.52
Upland Sedge	142.72	114.97	138.46	120.13	124.52
Forbs	147.18	286.03	311.01	167.70	254.91
Grasses	660.08	1037.30	1118.67	1037.20	1064.40
Graminoids	802.80	1152.27	1257.13	1157.33	1188.92
Total	949.98	1438.30	1568.14	1325.03	1443.83
Years 3-4	**May**	**Jun**	**Jul**	**Aug**	**Jun-Aug Mean**
Cool Short	194.36	300.70	278.70	272.36	283.92
Cool Middle	472.96	532.23	589.72	776.64	632.86
Wheatgrass	107.44	201.20	190.29	244.81	212.10
Warm Short	292.82	566.62	661.27	592.89	606.93
Upland Sedge	201.15	212.30	237.77	165.12	205.06
Forbs	200.60	302.49	218.44	142.72	221.22
Grasses	1067.58	1600.75	1719.98	1886.70	1735.81
Graminoids	1268.73	1813.05	1957.75	2051.82	1940.87
Total	1469.33	2115.54	2176.19	2194.54	2162.09

Table 4. Mean grazing season (June to August) herbage biomass (lbs/ac) by biotype categories on the sandy ecological site of the Biologically Effective management concept comparing years 3-4 to years 1-2, 1985-1986 to 1983-1986.

	Years 3-4 Herbage Biomass Composition		Years 1-2 Herbage Biomass Composition		Difference
Sandy Site	lbs/ac	%	lbs/ac	%	%
Cool Short	127.26	6.0	91.66	5.6	38.8
Cool Middle	450.56	21.1	359.03	22.1	25.5
Warm Tall	542.27	25.4	446.66	27.5	21.4
Warm Short	184.48	8.6	87.26	5.4	111.4
Upland Sedge	681.09	31.9	455.37	28.1	49.6
Forbs	149.06	7.0	183.09	11.3	-18.6
Grasses	1304.57	61.1	984.61	60.7	32.5
Graminoids	1985.66	93.0	1439.98	88.7	37.9
Total	2134.72		1623.07		31.5

Table 5. Mean grazing season (June to August) herbage biomass (lbs/ac) by biotype categories on the shallow ecological site of the Biologically Effective management concept comparing years 3-4 to years 1-2, 1985-1986 to 1983-1986.

	Years 3-4 Herbage Biomass Composition		Years 1-2 Herbage Biomass Composition		Difference
Shallow Site	lbs/ac	%	lbs/ac	%	%
Cool Short	259.28	18.3	175.43	17.3	47.8
Cool Middle	356.21	25.1	273.85	27.0	30.1
Wheatgrass	37.27	2.6	31.12	3.1	19.8
Warm Short	382.77	27.0	144.61	14.3	164.7
Upland Sedge	212.69	15.0	173.54	17.1	22.6
Forbs	172.26	12.1	214.54	21.2	-20.2
Grasses	1035.53	73.0	625.01	61.7	65.7
Graminoids	1248.22	87.9	798.55	78.8	56.3
Total	1419.48		1013.09		40.1

Table 6. Mean grazing season (June to August) herbage biomass (lbs/ac) by biotype categories on the silty ecological site of the Biologically Effective management concept comparing years 3-4 to years 1-2, 1985-1986 to 1983-1986.

	Years 3-4 Herbage Biomass Composition		Years 1-2 Herbage Biomass Composition		Difference
Silty Site	lbs/ac	%	lbs/ac	%	%
Cool Short	283.92	13.1	166.44	11.5	70.6
Cool Middle	632.86	29.3	408.67	28.3	54.9
Wheatgrass	212.10	9.8	137.77	9.5	54.0
Warm Short	606.93	28.1	351.52	24.3	72.7
Upland Sedge	205.06	9.5	124.52	8.6	64.7
Forbs	221.22	10.2	254.91	17.7	-13.2
Grasses	1735.81	80.3	1064.40	73.7	63.1
Graminoids	1940.87	89.8	1188.92	82.3	63.2
Total	2162.09		1443.83		49.7

Table 7. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Biologically Effective concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	397.73	637.66	760.51	670.20	826.89	698.80
Warm Season	179.90	217.06	304.43	333.21	300.86	302.53
Upland Sedge	165.99	199.29	204.99	175.74	127.28	137.21
Forbs	145.26	146.55	193.27	187.79	164.72	159.88
Grasses	577.63	854.72	1064.94	1003.41	1127.75	1001.33
Graminoids	743.62	1054.01	1269.93	1179.15	1255.03	1138.54
Total	888.88	1200.56	1463.20	1366.94	1419.75	1298.42

Table 8. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Traditional concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	308.46	483.96	606.10	515.39	548.70	542.12
Warm Season	123.98	157.64	244.45	287.08	222.68	241.69
Upland Sedge	168.26	226.16	237.83	222.50	151.45	126.55
Forbs	166.47	218.24	293.73	253.01	212.18	216.13
Grasses	432.44	641.60	850.55	802.47	771.38	783.81
Graminoids	600.70	867.76	1088.38	1024.97	922.83	910.36
Total	767.17	1086.00	1382.11	1277.98	1135.01	1126.49

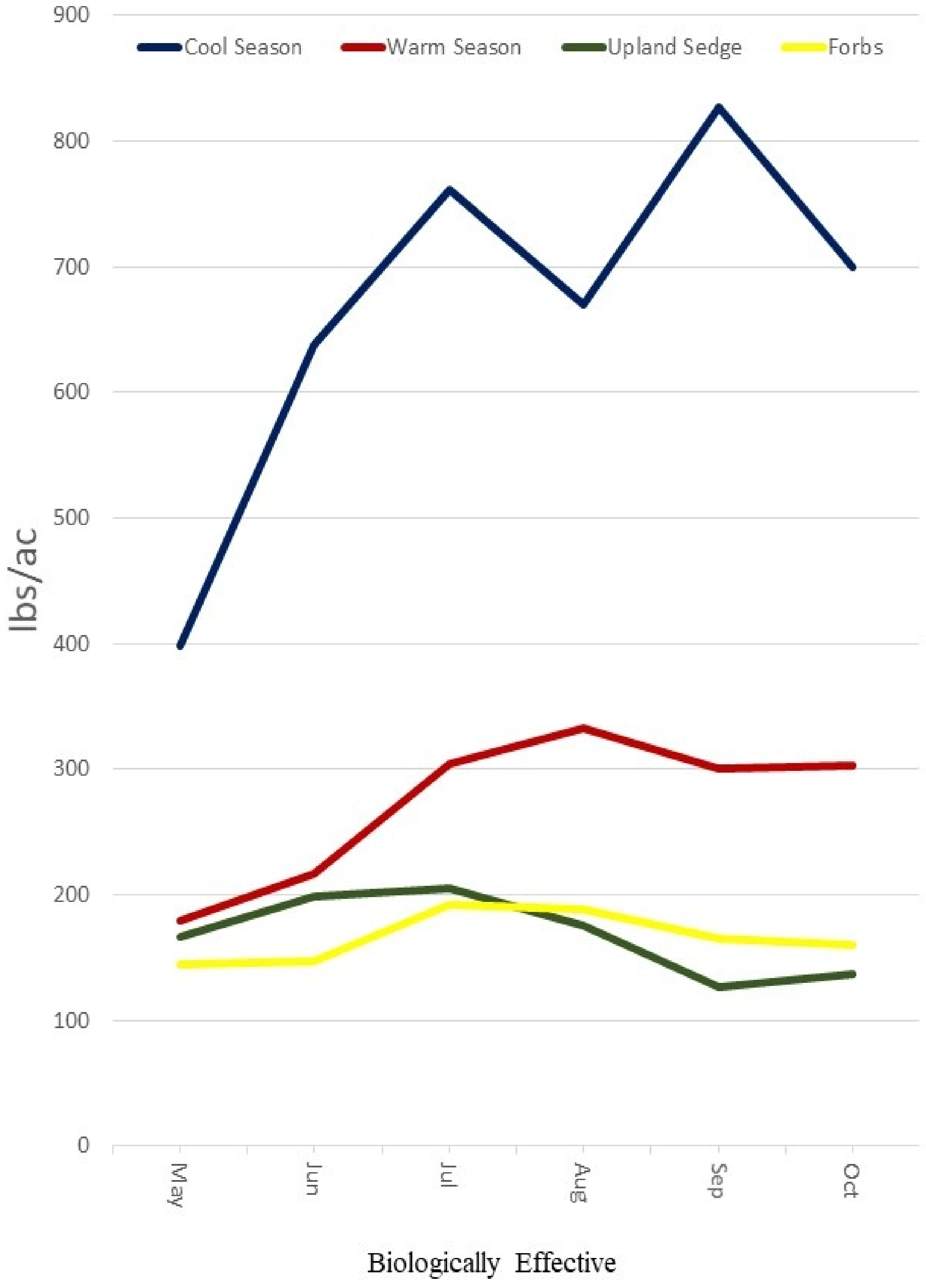

Figure 3. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Biologically Effective concept, 1983-2012.

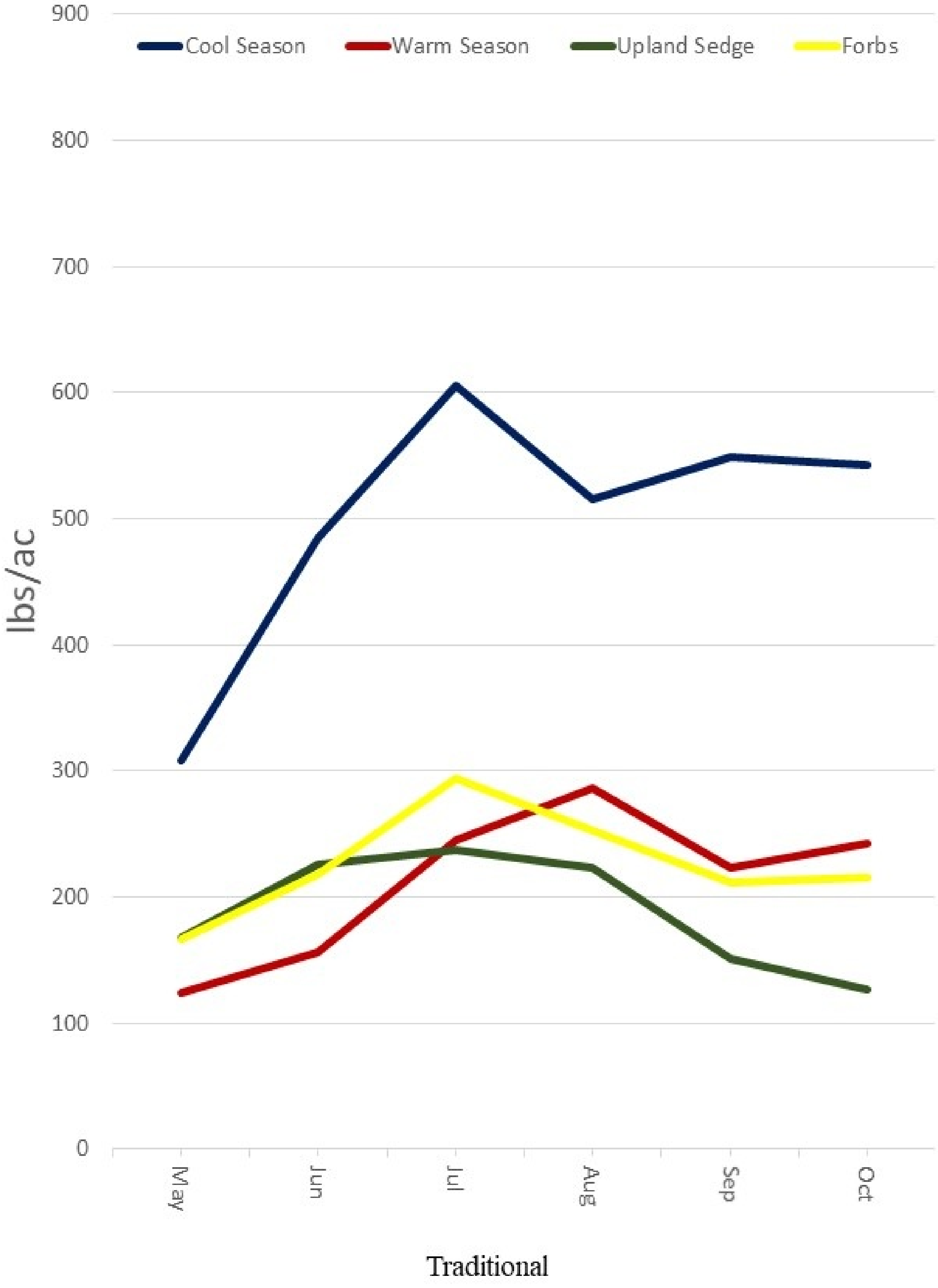

Figure 4. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Traditional concept, 1983-2012.

Table 9. Mean monthly herbage biomass (lbs/ac) produced on the silty sites of the Biologically Effective concept compared to that of the Traditional concept, 1983-2012.

Concept System	May	Jun	Jul	Aug	Sep	Oct
Cool Season						
Biologically Effective	397.73	637.66	760.51	670.20	826.89	698.80
Traditional	308.46	483.96	606.10	515.39	548.70	542.12
% Difference	28.9	31.8	25.5	30.0	50.7	28.9
Warm Season						
Biologically Effective	179.90	217.06	304.30	333.21	300.86	302.53
Traditional	123.98	157.64	244.45	287.08	222.68	241.69
% Difference	45.1	37.7	24.5	16.1	35.1	25.2
Upland Sedge						
Biologically Effective	165.99	199.29	204.99	175.74	127.28	137.21
Traditional	168.26	226.16	237.83	222.50	151.45	126.55
% Difference	-1.3	-11.9	-13.8	-21.0	-16.0	8.4
Forbs						
Biologically Effective	145.26	146.55	193.27	187.79	164.72	159.88
Traditional	166.47	218.24	293.73	253.01	212.18	216.13
% Difference	-12.7	-32.9	-34.2	-25.8	-22.4	-26.0

Table 10. Mean grazing season (June to October) herbage biomass (lbs/ac) by biotype categories on the silty ecological site of the Biologically Effective and Traditional concepts, 1983-2012.

	Biologically Effective		Traditional		
Silty Site	Herbage Biomass lbs/ac	Composition %	Herbage Biomass lbs/ac	Composition %	Difference %
Cool Season	718.81	53.3	539.25	44.9	33.3
Warm Season	291.62	21.6	230.71	19.2	26.4
Upland Sedge	168.90	12.5	192.90	16.1	-12.4
Forbs	170.44	12.6	238.66	19.9	-28.6
Grasses	1010.43	74.9	769.96	64.1	31.2
Graminoids	1179.33	87.4	962.86	80.2	22.5
Total	1349.77		1201.52		12.3

Table 11. Basal cover (%) of graminoids on the silty sites of the Biologically Effective and Traditional concepts, 1983-2012.

	Biologically Effective		Traditional		
Silty Site	Basal Cover %	Composition %	Basal Cover %	Composition %	Difference %
Cool Season	7.02	24.6	5.85	28.5	20.0
Warm Season	15.95	55.9	8.76	42.6	82.1
Upland Sedge	5.55	19.5	5.95	28.9	-6.7
Grasses	22.97	80.5	14.61	71.1	57.2
Graminoids	28.52		20.56		38.7

Table 12. Percent reduction of herbage biomass production resulting from partial defoliation treatments prior to grass tiller 3.5 new leaf stage.

Date of Defoliation Treatment	Swift Current grazing data	Mandan clipping data	Dickinson grazing data
1 May	-78%	-76%	-
15 May	-46%	-57%	-45%

Swift Current data from Campbell 1952.
Mandan data from Rogler et al. 1962 and Lorenz (per.com.).
Dickinson data from 1982 to 1987 grazing studies.

Table 13. Primary tiller density resulting from control (0%), 50%, and 25% defoliation treatments on seasonlong and twice-over grazing management strategies at end of two growing seasons associated with available mineral nitrogen and rhizosphere volume.

	Tiller density at end of two growing seasons			Mineral Nitrogen	Rhizosphere Volume
Management Strategy	Control $\#/m^2$	June 50% $\#/m^2$	June 25% $\#/m^2$	kg/ha	cm^3/m^3
Seasonlong	313.3	156.6	250.7	85.9	1552.3
Twice-over	469.9	501.3	814.4	199.2	5212.9

Table 14. Density (#/m^2) of major tiller types resulting from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies during two growing seasons.

Two Growing Seasons Defoliation Treatment Management Strategy	First Year Carryover Tillers #/m^2	Initiated Vegetative Tillers #/m^2	Terminated Vegetative Tillers #/m^2	Terminated Flowering Tillers #/m^2	Total Different Tillers #/m^2	Second Year Remaining Tillers #/m^2
Control						
Seasonlong	188.0	657.8	250.6	125.3	845.8	469.9
Twice-over	626.5	1472.3	720.4	720.5	2098.8	657.9
June 25%						
Seasonlong	250.6	657.9	313.3	219.3	908.5	375.9
Twice-over	595.2	1660.4	877.2	344.6	2255.6	1033.8

Table 15. Density (#/m^2) of tiller types resulting from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies during the first and second growing seasons.

First Growing Season Defoliation Treatment Management Strategy	Live tillers early May #/m^2	New tillers first season #/m^2	Total first season tillers #/m^2	Tillers at flower stage #/m^2	Dead tillers first season #/m^2	Live tillers late season #/m^2	New fall tillers #/m^2	Live tillers mid October #/m^2	Dead tillers winter period #/m^2
Control									
Seasonlong	281.9	0.0	281.9	94.0	62.7	125.3	94.0	219.3	0.0
Twice-over	877.1	62.7	939.8	344.6	250.6	344.6	250.6	595.2	31.3
June 25%									
Seasonlong	438.6	31.3	469.9	94.0	156.6	219.3	125.3	344.6	0.0
Twice-over	971.1	62.7	1033.8	156.6	407.2	469.9	344.6	814.5	188.0

Second Growing Season Defoliation Treatment Management Strategy	Carry over tillers #/m^2	New tillers early spring #/m^2	Live tillers early May #/m^2	New tillers second season #/m^2	Total second season tillers #/m^2	Tillers at flower stage #/m^2	Dead tillers second season #/m^2	Live tillers late season #/m^2	New fall tillers #/m^2	Live tillers mid October #/m^2
Control										
Seasonlong	219.3	188.0	407.2	125.3	532.5	31.3	188.0	313.3	156.6	469.9
Twice-over	563.9	469.9	1033.8	250.6	1284.4	375.9	438.6	469.9	188.0	657.8
June 25%										
Seasonlong	344.6	0.0	344.6	188.0	532.5	125.3	156.6	250.6	125.3	375.9
Twice-over	626.5	469.9	1096.4	188.0	1284.4	188.0	281.9	814.5	219.3	1033.8

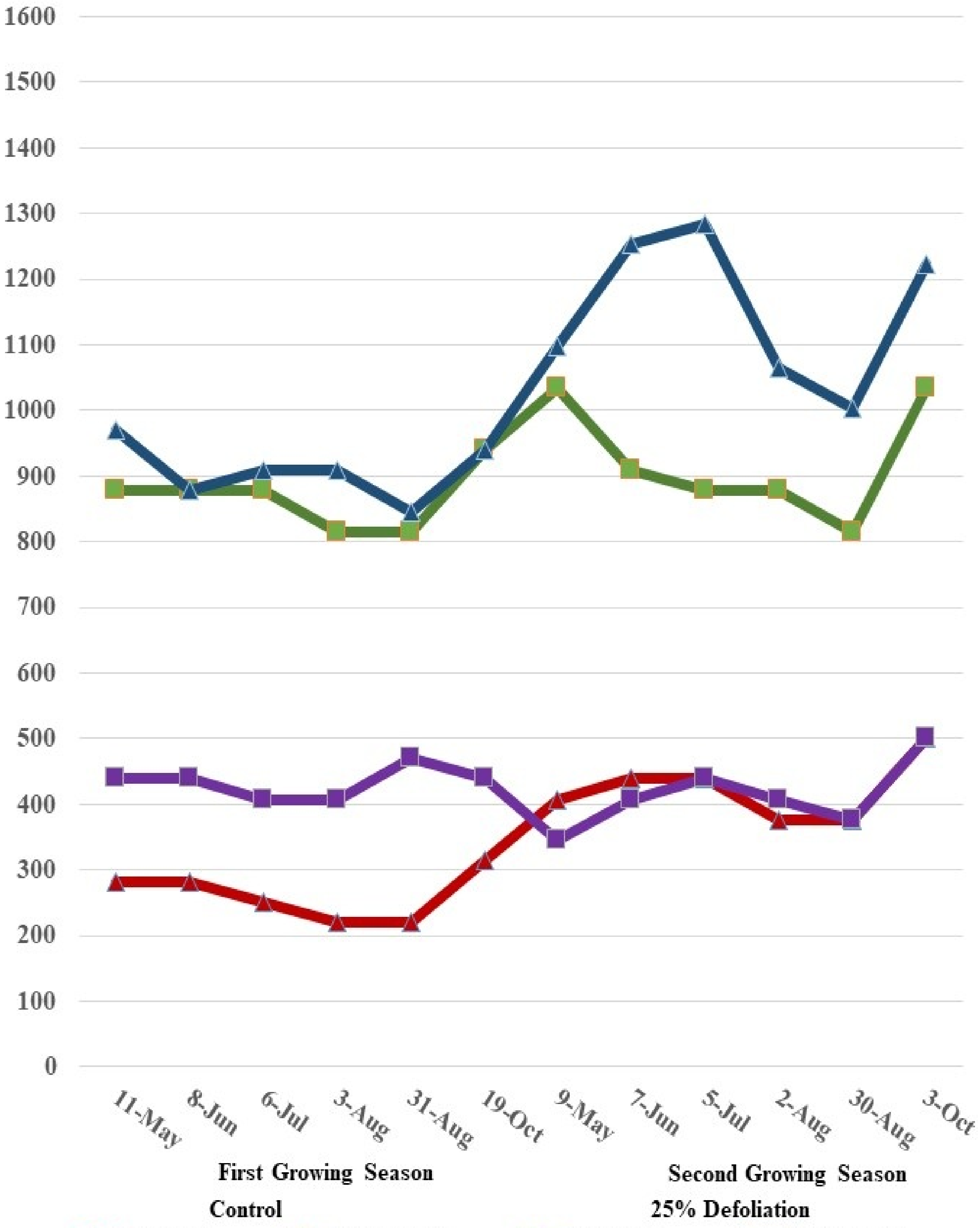

Figure 5. Monthly tiller density per square meter on the control and mid June 25% defoliation treatments during the first and second growing seasons.

Table 16. Density (#/m^2) of mean monthly tillers of pregrazing and grazing periods from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies during two growing seasons.

	First Growing Season		Second Growing Season	
Two Growing Seasons Defoliation Treatment Management Strategy	Pregrazing Tillers May #/m^2	Grazing Period Tillers Jun-mid Oct #/m^2	Pregrazing Tillers May #/m^2	Grazing Period Tillers Jun-mid Oct #/m^2
Control				
Seasonlong	281.9	245.4	407.2	391.6
Twice-over	877.1	814.5	1033.8	892.8
June 25%				
Seasonlong	438.6	402.0	344.6	391.6
Twice-over	971.1	824.9	1096.4	1117.3

Table 17. Density (#/m^2) of initiated vegetative tillers from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies during two growing seasons.

Two Growing Seasons Defoliation Treatment Management Strategy	Spring Tillers mid Apr-May #/m^2	Summer Tillers Jun-Jul #/m^2	Fall Tillers Aug-mid Oct #/m^2	Total Vegetative Tillers #/m^2
Control				
Seasonlong	313.3	94.0	250.6	657.9
Twice-over	877.1	156.6	438.6	1472.3
June 25%				
Seasonlong	250.6	156.6	250.6	657.9
Twice-over	1033.8	62.7	563.9	1660.4

Table 18. Density (#/m^2) of terminated vegetative tillers before reaching maturity and terminated lead tillers after flowering from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies during two growing seasons.

Two Growing Seasons Defoliation Treatment Management Strategy	Vegetative Tillers Spring mid Apr-May #/m^2	Vegetative Tillers Grazing Period Jun-mid Oct #/m^2	Lead Tiller Past Flowering Jun-mid Oct #/m^2	Winter Dormancy Period #/m^2	Total Terminated Tillers #/m^2
Control					
Seasonlong	0.0	250.6	125.3	0.0	375.9
Twice-over	281.9	407.2	720.5	31.3	1440.9
June 25%					
Seasonlong	0.0	313.3	219.3	0.0	532.6
Twice-over	125.3	563.9	344.6	188.0	1221.8

Table 19. Density (#/m^2) of mean monthly tiller types from control (0%) and 25% defoliation treatments on seasonlong and twice-over management strategies during two growing seasons.

Two Growing Seasons	Traditional Seasonlong		Twice-over Rotation	
Tiller Type	Control #/m^2	mid June 25% #/m^2	Control #/m^2	mid June 25% #/m^2
Reproductive	62.7	99.2	352.5	172.3
Vegetative	146.2	159.2	266.3	543.0
Secondary	133.1	156.6	279.3	334.2
Total Tillers	342.0	415.1	898.0	1049.4

Table 20. Density (#/m^2) of forage tillers between the 4 leaf stage and flower stage from control (0%) and 25% defoliation treatments on seasonlong and twice-over grazing management strategies means of two growing seasons.

	Biweekly Periods								
Two Growing Seasons Defoliation Treatment Management Strategy	E May	M May	E Jun	M Jun	E Jul	M Jul	E Aug	L Aug	M Oct
Tiller Type	#/m^2	#/m^2	#/m^2	#/m^2	#/m^2	#/m^2	#/m^2	#/m^2	#/m^2
Control									
Seasonlong									
Reproductive	15.6	31.3	47.0	15.6	15.6	0.0	0.0	0.0	0.0
Vegetative	15.6	47.0	78.3	109.6	156.6	156.6	156.6	156.6	156.6
Secondary	0.0	0.0	0.0	15.6	15.6	31.3	15.6	47.0	78.3
Total	31.3	78.3	125.3	141.0	188.0	188.0	172.3	203.6	235.0
Twice-over									
Reproductive	125.3	203.6	281.9	281.9	156.6	47.0	31.3	0.0	0.0
Vegetative	47.0	78.3	188.0	250.6	266.3	266.3	235.0	235.0	235.0
Secondary	31.3	141.0	78.3	62.7	109.6	141.0	172.3	125.3	156.6
Total	203.6	422.9	548.2	595.2	532.5	454.2	438.6	360.3	391.6
June 25%									
Seasonlong									
Reproductive	15.6	47.0	62.7	47.0	31.3	0.0	0.0	0.0	0.0
Vegetative	47.0	94.0	141.0	156.6	156.6	156.6	156.6	125.3	125.3
Secondary	0.0	0.0	0.0	0.0	31.3	31.3	31.3	109.6	94.0
Total	62.7	141.0	203.6	203.6	219.3	188.0	188.0	234.9	219.3
Twice-over									
Reproductive	78.3	141.0	172.3	141.0	62.7	15.6	0.0	0.0	0.0
Vegetative	188.0	375.9	532.5	579.5	516.9	516.9	516.9	485.6	485.6
Secondary	15.6	0.0	15.6	47.0	203.6	156.6	141.0	141.0	203.6
Total	281.9	516.9	720.5	767.5	783.2	689.2	657.8	626.6	689.2

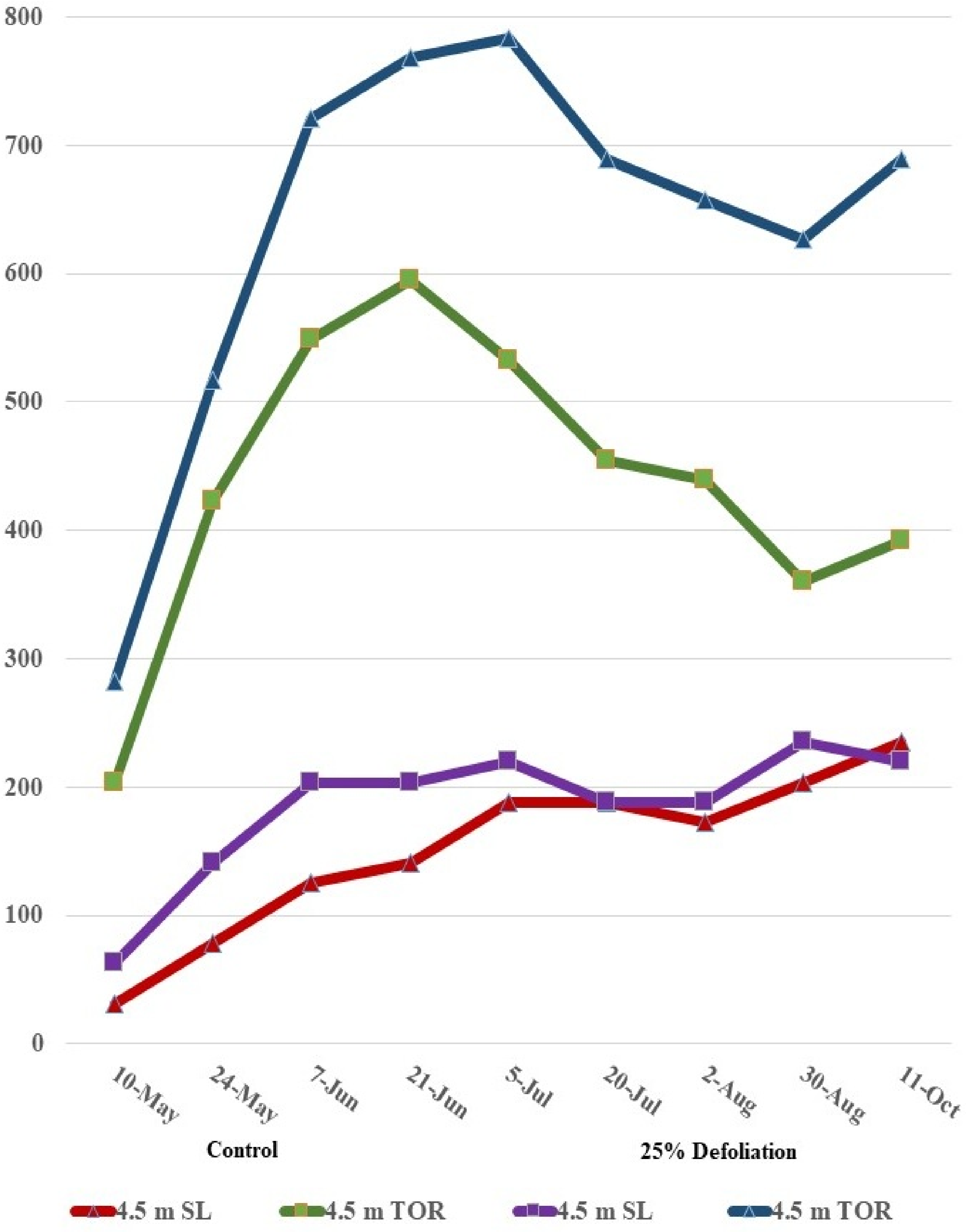

Figure 6. Density (#/m^2) of forage tillers between the 4 leaf stage and flower stage.

Table 21. Density (#/m^2) and percentage of forage tillers and not forage tillers from control (0%) and 25% defoliation treatments on seasonlong and twice-over management strategies.

	First Grazing Period early Jun to mid Jul			Second Grazing Period mid Jul to mid Oct			Total Grazing Period early Jun to mid Oct		
Two Growing Seasons Defoliation Treatment Management Strategy	Forage Tillers #/m^2	Not Forage Tillers #/m^2	Total Tillers #/m^2	Forage Tillers #/m^2	Not Forage Tillers #/m^2	Total Tillers #/m^2	Forage Tillers #/m^2	Not Forage Tillers #/m^2	Total Tillers #/m^2
Control									
Seasonlong	160.6	191.9	352.5	199.7	134.5	334.2	179.0	162.5	341.5
% of total	45.6%	54.4%		59.8%	40.2%		52.4%	47.6%	
Twice-over	532.5	352.5	885.0	411.2	471.2	882.4	474.4	409.0	883.4
% of total	60.2%	39.8%		46.6%	53.4%		53.7%	46.3%	
June 25%									
Seasonlong	203.6	219.3	422.9	207.6	225.7	433.3	208.1	221.1	429.2
% of total	48.1%	51.9%		47.9%	52.1%		48.5%	51.5%	
Twice-over	740.1	340.7	1080.8	665.7	331.5	997.2	704.9	325.8	1030.7
% of total	68.5%	31.5%		66.8%	33.2%		68.4%	31.6%	

Table 22. Mean monthly native (cool and warm season) grass biomass (lbs/ac) on silty ecological sites of the seasonlong and twice-over management strategies, 1983-2012.

Silty Site	Jun	Jul	Aug	Sep	Oct	Mean
Twice-over	854.72	1064.94	1003.41	1127.75	1001.33	1010.43
Seasonlong	641.60	850.55	802.47	771.38	783.81	769.96
Difference	213.12	214.39	200.94	356.37	217.52	240.47
% increase from twice-over	33.2	25.2	25.0	46.2	27.8	31.2

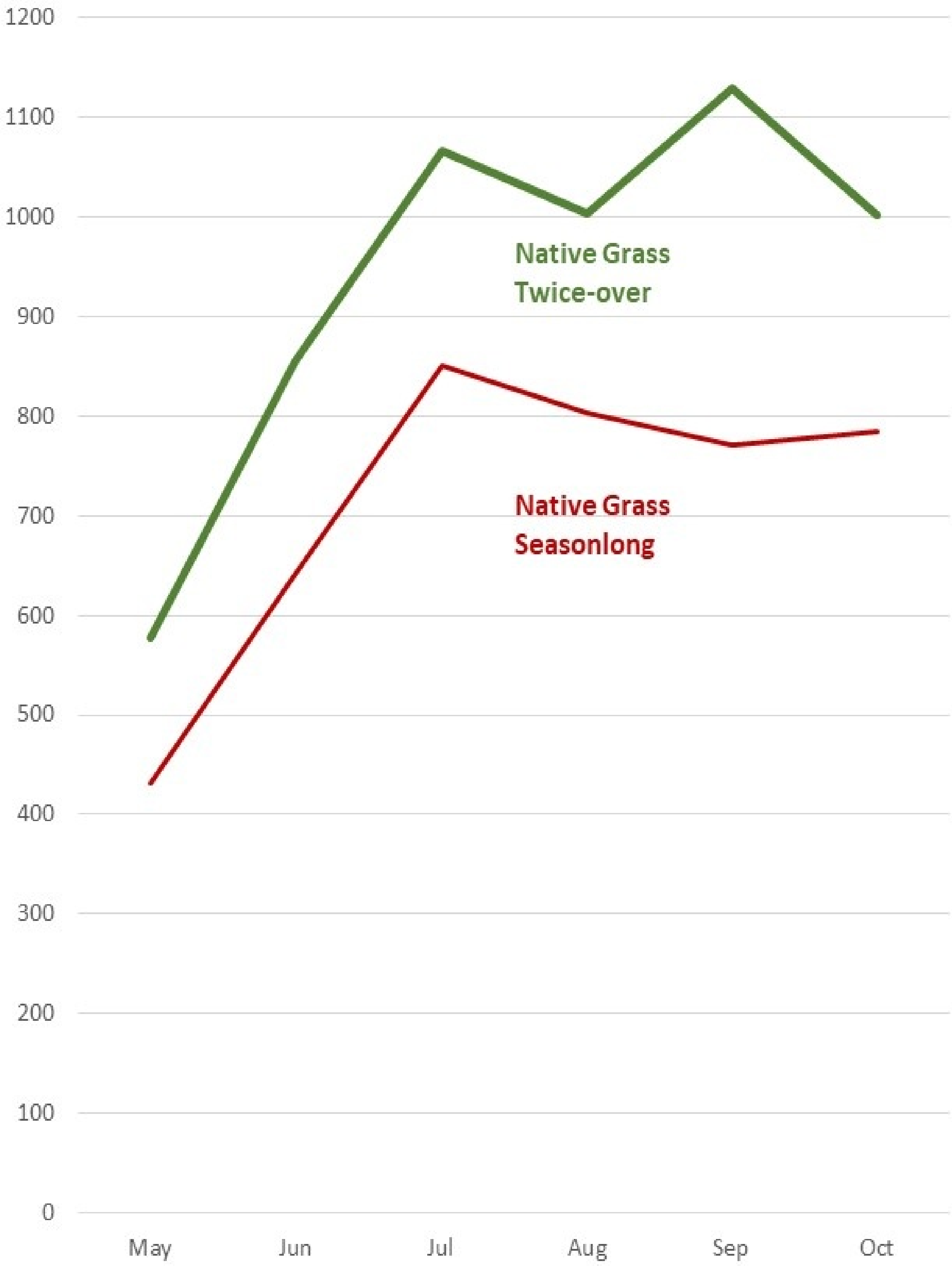

Figure 7. Mean monthly native grass biomass (lbs/ac) on seasonlong and twice-over management strategies.

Table 23. Percent crude protein on native rangeland summer pastures.

Grass Biotype	May		Jun		Jul		Aug		Sep		Oct
	8	24	8	24	8	24	8	24	8	24	15
Upland Sedge		13.8	13.6	11.7	10.4	8.9	7.8	7.6	8.0	6.8	6.9
Cool Season											
Lead Tillers		16.4	14.8	13.7	10.9	8.9	6.9	6.6	5.3	6.4	6.0
Secondary Tillers					10.2		11.6		13.2	12.1	6.1
Warm Season											
Lead Tillers		15.6	13.9	12.2	10.8	8.9	7.3	7.1	6.5	4.5	4.4
Secondary Tillers							8.9		10.0	8.2	5.7
Native Grass											
Lead Tillers		15.8	14.3	12.9	10.8	8.9	7.3	7.1	6.6	5.9	5.8
Secondary Tillers					10.2		10.3		11.6	10.2	5.9

Data summarized from Whitman et al. 1951 and Sedivec 1999.

Table 24. Percent phosphorus on native rangeland summer pastures.

Grass Biotype	May		Jun		Jul		Aug		Sep		Oct
	8	24	8	24	8	24	8	24	8	24	15
Upland Sedge		0.169	0.160	0.166	0.154	0.122	0.103	0.105	0.110	0.083	0.090
Cool Season											
Lead Tillers		0.238	0.256	0.238	0.217	0.188	0.153	0.147	0.122	0.120	0.118
Secondary Tillers					0.274	0.284	0.275	0.228	0.243	0.258	
Warm Season											
Lead Tillers		0.248	0.293	0.281	0.245	0.219	0.181	0.172	0.147	0.105	0.081
Secondary Tillers						0.285	0.270	0.270	0.254	0.251	
Native Grass											
Lead Tillers		0.232	0.261	0.252	0.222	0.194	0.158	0.153	0.125	0.108	0.096
Secondary Tillers					0.274	0.285	0.273	0.249	0.249	0.255	

Data summarized from Whitman et al. 1951.

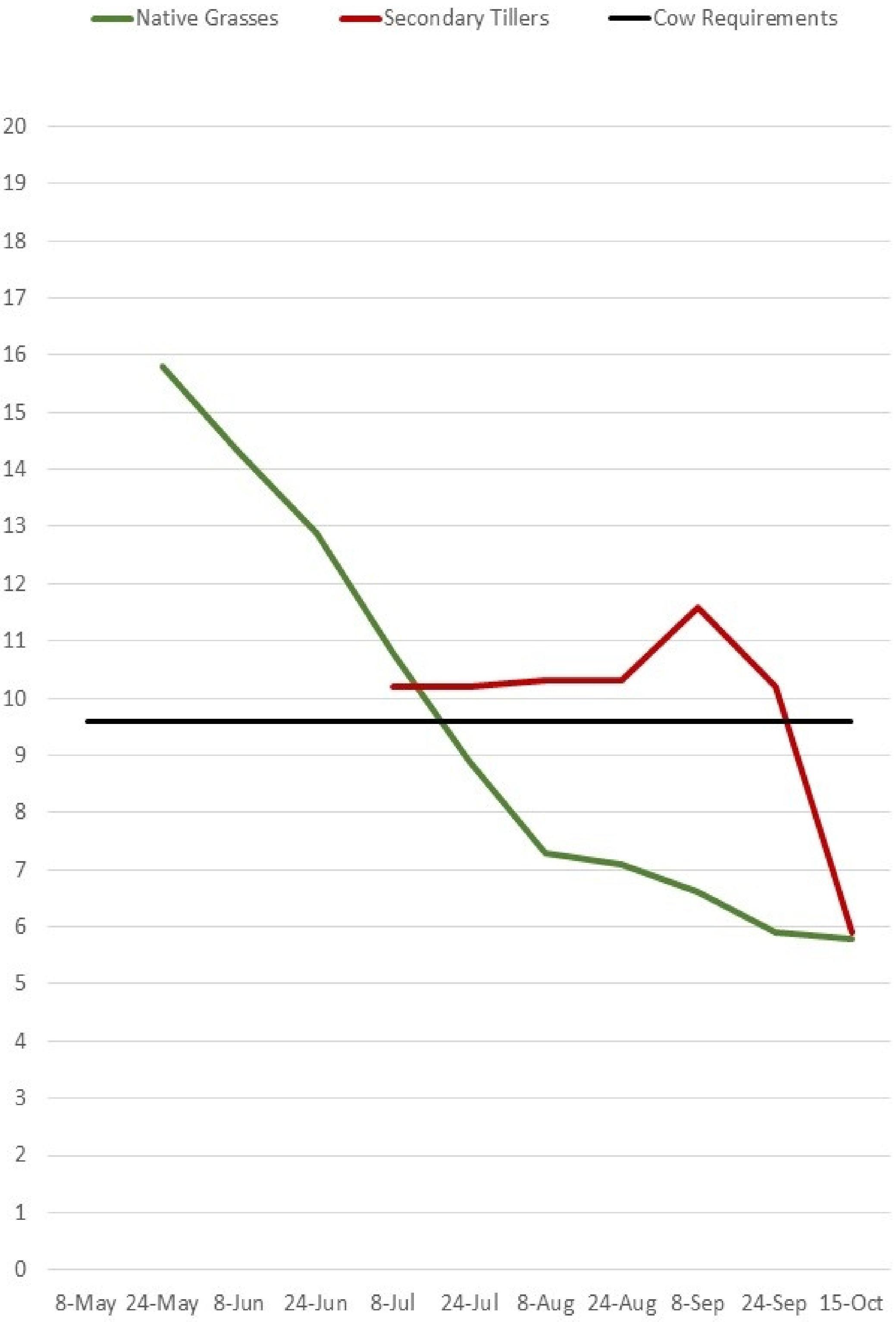

Figure 8. Percent Crude Protein of lead tillers and secondary tillers during the growing season. Data from Whitman et al. 1951 and Sedivec 1999.

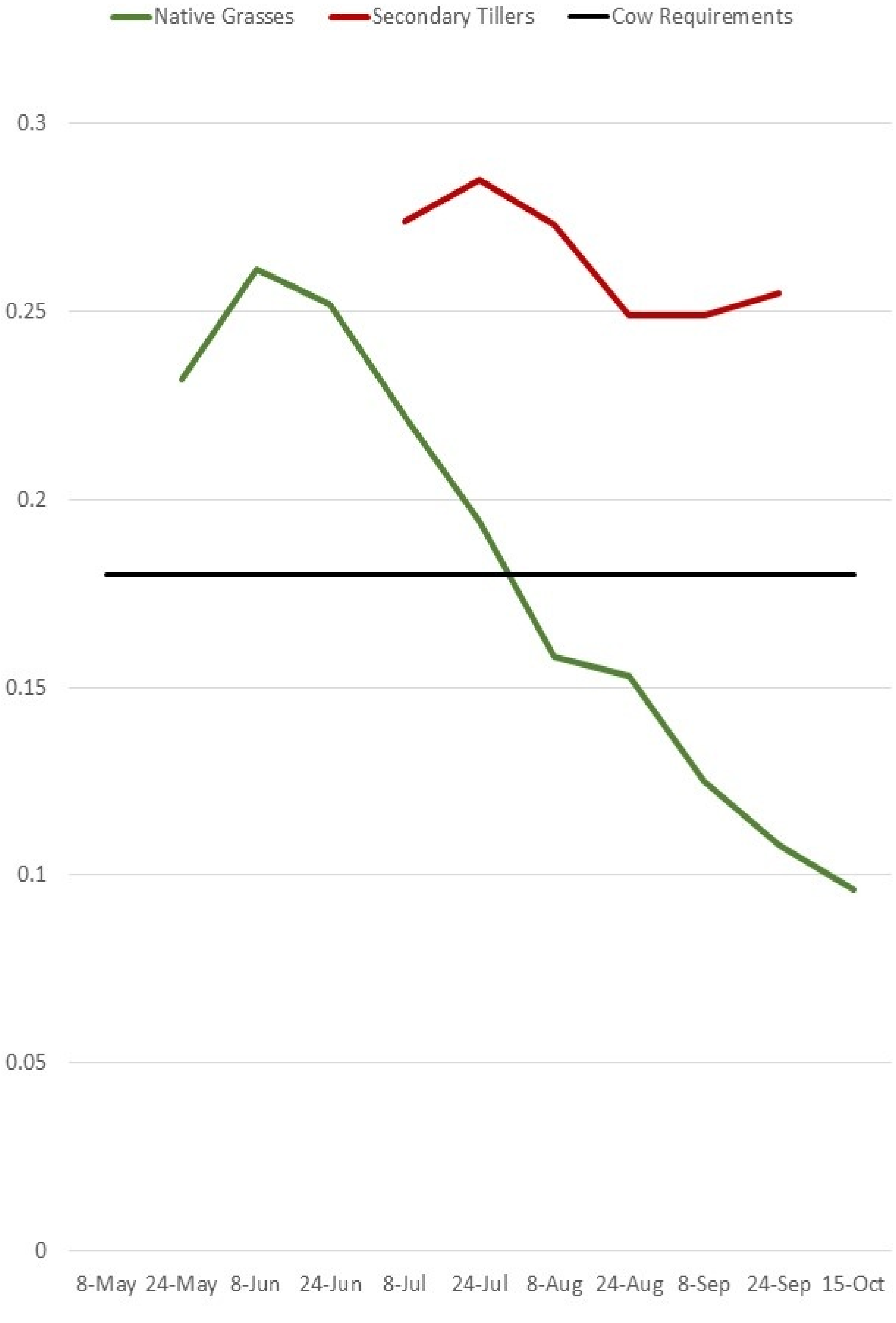

Figure 9. Percent Phosphorus of lead tillers and secondary tillers during the growing season. Data from Whitman et al. 1951.

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Rhizosphere Organisms:
An Indispensable Biotic Component of the Northern Mixed Grass Prairie

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

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component part and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains. The introduction to this study can be found in report DREC 16-1093 (Manske 2016).

Grass vegetation, rhizosphere organisms, and domesticated graminivores are indispensable biotic components of a functional rangeland ecosystem. Grazing graminivores depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short carbon chain energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing graminivores. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing graminivores on which they depend.

The three indispensable biotic components of rangeland ecosystems: Grass Vegetation, Rhizosphere Organisms, and Domesticated Graminivores will each be quantitatively described in separate companion reports. This report will provide scientific information on rhizosphere organisms as indispensable biotic components of grassland ecosystems.

Elucidation of the Microbial Rhizosphere

The scientific research and resulting general information on the cropland (mixed soil) microbial rhizosphere and the grassland (intact soil) microbial rhizosphere have unwittingly been intermingled causing serious confusion. All of the microbes in cropland are free-living in the soil edaphosphere (earth sector or zone). A small proportion of microbes in grassland soils are free-living in the edaphosphere, with the greatest amount of microbes living in the rhizosphere (root sector or zone).

The majority of the basic research of grassland rhizosphere microbes was conducted mainly in the United States from the late 1970's to the early 1990's with no program for followup applied research. The majority of the basic research on microbial processes in cropland soils for assessing soil quality was primarily conducted in European Union countries after the adoption of the Treaty on Biological Diversity of Rio de Janeiro in 1992 until around 2006 with no program for followup applied research.

The microbes in cropland mixed soils in which annual plants grow are all free-living. Some of these microbes do not associate with plants. Two types of free-living microbes associate with plants, some of these microbes are plant-detrimental (pathogenic) and some are plant-beneficial. The free-living plant-beneficial microbes live in a zone of unaltered soil surrounding active annual roots. This volume of loose soil is called a rhizosphere which exists only as long as the root remains active.

The microbes in intact soils of grasslands in which perennial plants grow are symbiotic with the plants and inhabit a cylinder of soil particles bonded by fungal secreted adhesive polysaccharides that surrounds perennial roots are also called a rhizosphere. The numerous types of rhizosphere organisms are organized along a trophic hierarchy with a means of "communication" among the microbes and with the plant.

Confusion has been created by using the same term to describe these different microbial structures. The rhizosphere in croplands is a zone of loose soil around an annual root in which bunches of free-living plant-beneficial independent microbes congregate. The rhizosphere in grasslands is a constructed chamber of bonded soil particles around a perennial root that is the summer quarters for numerous trophic levels of interacting symbiotic microbes. The latter description of the microbial rhizosphere will be used in this report.

Indispensable Rhizosphere Organisms

The microbial rhizosphere is a cylinder of bonded soil around active roots of perennial grassland plants and is comprised of resident organisms and frequent regular visiting organisms. The resident organisms are bacteria, protozoa, and endomycorrhizal fungi and the visiting organisms are nematodes, springtails, and mites (Elliot 1978, Anderson et al. 1981, Harley and Smith 1983, Curl and Truelove 1986, Whipps 1990, Campbell and Greaves 1990) and another resident organism is ectomycorrhizal fungi (Caesar-TonThat et al. 2001b, Manske and Caesar-TonThat 2003, Manske 2007b). The activity of rhizosphere organisms increases along the trophic hierarchy, starting with the resident bacteria. The numerous types of bacteria lack chlorophyll and have low carbon content. Bacteria are microscopic single celled saprophytic organisms that collectively consume large quantities of soil organic matter and are major primary producers of the rhizosphere. Increases in biomass and activity of the bacteria trophic level elevates the concentration of respiratory carbon dioxide (CO_2) resulting in stimulation of activity in the other rhizosphere organisms. Protozoa are single celled microorganisms that are mainly small amoeba in grassland soils and feed primarily on bacteria.

The slightly larger rhizosphere organisms are mobile and move among various rhizosphere structures. Nematodes are a diverse group of small nonsegmented worms. Most nematodes feed primarily on bacteria or fungi, some feed on protozoa, and some eat other nematodes. Springtails are among the most abundant insect in grassland soils that travel among rhizosphere structures. Minute springtails ingest considerable quantities of soil organic matter in order to eat fungi and bacteria. Mites are small eight-legged arachnids that travel among rhizosphere structures and feed on fungi, nematodes, small insects, and other mites. Mites help distribute fungus spores and bacteria through the soil by carrying them on their exoskeleton.

Two types of fungi are resident organisms of the rhizosphere; Endomycorrhizal fungi and Ectomycorrhizal fungi. Endomycorrhizal fungi are also major primary producers of the rhizosphere and are achlorophyllous saprophytes that live on dead organic matter and cannot fix carbon for energy. Endomycorrhizal fungi develop arbuscules, vesicles, and hyphae within root tissue of the host plant (Harley and Smith 1983) and secrete adhesive polysaccharides that bond soil particles around grass roots forming the structural environment for all rhizosphere organisms. The adhesive polysaccharides also bind soil into aggregates resulting in increased soil pore spaces, increased water holding capacity, and increased rooting depth. Endomycorrhizal fungi also move phosphorus, other macro and micro mineral nutrients, and water through the hyphae to the grass roots for absorption (Moorman and Reeves 1979, Harley and Smith 1983, Allen and Allen 1990, Box and Hammond 1990, Marschner 1992, Koide 1993, Marschner and Dell 1994, Smith and Reed 1997).

Ectomycorrhizal fungi develop a sheath around the grass root with hyphae that do not enter the tissue of the host plant (Harley and Smith 1983) and secrete large amounts of adhesive polysaccharides forming water-stable aggregates in soil that are water permeable but not water soluable. The increased soil aggregation improves soil quality, increases soil oxygenation, increases water infiltration, and decreases 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 2007b).

The bacteria and fungi are the microflora saprotrophic organisms at the bottom of the food chain and makeup the greatest biomass of the rhizosphere. Both bacteria and fungi contain high proportions of nitrogen in relation to their carbon content. The microfauna trophic level organisms with normal ratios of carbon to nitrogen, graze on bacteria or fungi and ingest greater quantities of nitrogen than they need for a balanced diet based on energy (carbon); the excess nitrogen is excreted as ammonium (NH_4). The endomycorrhizal fungi can nitrify the excreted ammonium into nitrate (NO_3) and pass either form of mineral nitrogen into the grass plant through its endophytic vesicles and arbuscules.

The elevated rhizosphere organism activity caused by the increase in available short carbon chain energy exudated from the grass plant following partial defoliation by graminivores results in a greater quantity of organic nitrogen mineralized into inorganic 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).

Biogeochemical Processes

Biogeochemical processes performed by rhizosphere microorganisms renew the nutrient flow activities in ecosystem soils of renewable natural resources. Biogeochemical processes transform stored essential elements from organic forms into plant usable inorganic forms. Biogeochemical processes capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen with assistance from active live plants and transform the replacement essential elements into storage as organic forms for later use. Biogeochemical processes decompose complex unusable organic material into compounds and then into reusable essential elements (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).

The quantity of biogeochemical processes conducted in grassland ecosystems is dependent on the rhizosphere volume and microorganism biomass (Coleman et al. 1983). Rhizosphere volume and microorganism biomass are limited by access to simple carbohydrate energy (Curl and Truelove 1986). Healthy grass plants produce double the quantity of leaf biomass (Crider 1955, Coyne et al. 1995), capture and fix large amounts of carbon during photosynthesis, and produce carbohydrates in quantities greater than the amount needed for normal growth and maintenance (Coyne et al. 1995). Partial defoliation of grass tillers at vegetative phenological growth stages by large grazing graminivores causes greater quantities of exudates containing simple carbohydrates to be released from the grass 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 quantities of biogeochemical cycling of essential elements (Coleman et al. 1983, Biondini et al. 1988, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

Rhizosphere Biomass effects Essential Elements

The essential elements are required for life to exist by ensuring growth and development of organisms and the maintenance of all life functions. Microbes and plants require seventeen elements and animals require twenty one elements. Sixteen of these essential elements are required by all grassland organisms. Microbes, plants, and animals require very large amounts of the same four major essential elements: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). Grassland organisms also require large amounts of the same five macronutrients: calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S). Animals require one additional macronutrient: sodium (Na). Warm season plants and cacti use sodium (Na). All grassland organisms require very small amounts of the same seven micronutrients or trace elements: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chlorine (Cl), molybdenum (Mo), and nickel (Ni). Plants require one additional micronutrient: boron (B). A few plants and rhizobia use cobalt (Co). Animals require four additional micronutrients: iodine (I), selenium (Se), chromium (Cr), and cobalt (Co) (tables 1 and 2).

Table 1. Essential Elements Required by Microbes and Plants.

Major Essential Elements

Carbon (C), Hydrogen (H), Nitrogen (N), and Oxygen (O).

Minor Essential Elements

- Macronutrients
  - Phosphorus (P), Potassium (K),
  - Calcium (Ca), Magnesium (Mg), Sulfur (S)
- Micronutrients
  - Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu),
  - Boron (B), Chlorine (Cl), Molybdenum (Mo), Nickel (Ni)

Table 2. Essential Elements Required by Animals.

Essential Nutrients

Crude Protein, Energy, Water, Vitamins

Major Essential Elements

Carbon (C), Hydrogen (H), Nitrogen (N), and Oxygen (O).

Minor Essential Elements

- Macrominerals
  - Calcium (Ca), Phosphorus (P), Potassium (K),
  - Magnesium (Mg), Sulfur (S), Sodium (Na), Chlorine (Cl)
- Microminerals
  - Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu),
  - Iodine (I), Cobalt (Co), Selenium (Se),
  - Molybdenum (Mo), Chromium (Cr), Nickel (Ni)

Recycling Essential Elements

Perpetuation of life on earth requires that the major and minor essential elements be reused over and over. Recycling of the essential elements is performed by microorganisms associated with renewable natural resources (rangelands, grasslands, croplands, forestlands, and fisheries). When greater quantities of essential elements are used or lost than the quantities accumulated, the ecosystem degrades (declines). When greater quantities of essential elements are accumulated than the quantities used, the ecosystem aggrades (improves).

Some loss of essential elements from a grassland ecosystem occurs naturally. The metabolic processes of respiration in soil organisms, plants, livestock, wildlife, and insects results in a loss of essential elements as carbon dioxide, water vapor, and heat energy. Essential elements are removed from a grassland ecosystem as weight biomass produced by insects and wildlife. The essential elements transferred from grass plants to grazing livestock and used for animal growth are removed from the ecosystem (Gibson 2009).

The small proportion of the ecosystem essential elements that are lost or removed annually need to be replenished by capturing input essential elements from the surrounding environment through ecosystem processes. The biogeochemical processes associated with active live plants and soil microorganisms can capture replacement quantities for the lost major essential elements of carbon, hydrogen, nitrogen and oxygen.

The ecosystem input source for energy is radiant light from the sun. Radiant energy from the sun is necessary for photosynthesis. In the Northern Plains, sunlight reaching the plants has a small reduction resulting from about 30% cloud cover. The intensity of sunlight can be greatly reduced by shading from taller grasses and shrubs. Nondefoliated live and standing dead leaves of grasses reduce light penetration to a similar degree as shrubs, even though shrub leaves are flat and wide and grass leaves are erect and linear (Kochy 1999). The light levels penetrating the leaf canopy can be about 20% of the light levels above the canopy (Peltzer and Kochy 2001).

The ecosystem input source for carbon is atmospheric carbon dioxide (CO_2). Atmospheric carbon dioxide composes about 0.03% of the gasses in the atmosphere at concentrations of around 370 to 385 mg/kg. The carbon dioxide is fixed with hydrogen from soil water during the plant process of 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 posses chlorophyll and has low biological costs to the ecosystem resources (Manske 2011b). Some of the short carbon chain energy is exudated into the rhizosphere to help increase the soil microorganism biomass. When the dead plant material is decomposed by the soil microbes, some of the carbon is combined with oxygen to form carbon dioxide gas which is volatilized and released back into the atmosphere.

The ecosystem input source of hydrogen is soil water (H_20) which is infiltrated precipitation water. Soil water is absorbed through the roots and distributed throughout the plant within the xylem vascular tissue. When the rate of water absorption by the roots is less than the rate of water loss from transpiration through stomata openings, plant tissue develops water stress (Brown 1995). Plant water stress limits growth. In western North Dakota, the six month perennial plant growing season has a long-term periodicity rate of water deficiency conditions at 32.7% for the mean of 2.0 months with water deficiency per growing season (Manske et al. 2010). Hydrogen is released into the soil during the early stages of soil organic matter decomposition.

The ecosystem input source for nitrogen is wet deposition of nitrogen oxides following lightning. Lightning discharges cause atmospheric nitrogen (N_2) and oxygen (O_2) to combine and produce nitrogen oxides, mainly nitric acid (NO) and dinitrogen oxide (N_2O), that are deposited in precipitation (Manske 2009). The ambient amount of nitrogen deposition in temperate regions from natural sources is around 5 to 6 pounds per acre per year (Brady 1974). The source of nitrogen for grass growth is mineral nitrogen (NO_3, NH_4) mineralized from the soil organic nitrogen by rhizosphere organisms. Low quantities of available soil mineral nitrogen below 100 lbs/ac (112 kg/ha) is the major limiting factor of herbage growth on rangelands (Wight and Black 1979). However, rangeland soils are not deficient of nitrogen. Most of the nitrogen is immobilized in the soil as organic nitrogen. Soil organic nitrogen must be mineralized by rhizosphere organisms to become plant usable mineral nitrogen. The quantity of rhizosphere organisms is the limiting factor in rangeland ecosystems low in mineral nitrogen. Biomass and activity of organisms in the rhizosphere are limited by access to energy from simple carbon chains which can be exudated from grass lead tillers with partial defoliation by grazing graminivores when grass tillers are at vegetative growth stages. Transformation of nitrogen from organic nitrogen to 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, b).

The ecosystem input source for oxygen is carbon dioxide, nitrogen oxides, and water. Atmospheric oxygen composes about 20.95% of the gasses in the atmosphere. Oxygen content in soil air is at a much lower concentration. The oxygen cycle between the biotic and abiotic components of the ecosystem 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 known to be limiting on rangeland ecosystems.

The ecosystem input source for the six macronutrients and 12 micronutrients required by microbes, plants, and animals is weathered parent material. The elemental content of the parent material greatly influence the quantity of macro- and micronutrients in the soil. It is possible to remove macro- and micronutrients from soil at a faster rate than the rate of parent material weathering. The other natural mechanisms of transporting additional macro- and micronutrients into a region are glacial, flood, earthquake, and volcanic deposition.

Management practices that permit the use or loss of greater quantities of essential elements than the quantities of replacement essential elements captured cause grassland ecosystems to degrade. The single most important factor that permits the capture of greater quantities of replacement essential elements than the quantities used or lost is a large biomass of active soil microorganisms (Coleman et al. 1983, Schimel, Coleman, and Horton 1985, Cheng and Johnson 1998). The soil microorganisms are the renewable portion of grassland natural resources.

Aggradation of grassland ecosystems occurs when beneficial management practices cause increased quantities of labile (readily available) simple carbon chain energy from grass lead tillers at vegetative growth stages to be exudated (released) through the roots into the rhizosphere providing the limiting nutrient necessary for microorganism biomass to increase (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990, Hamilton and Frank 2001, Manske 2011b). The resulting increased biomass of soil microorganisms are able to decompose and mineralize greater quantities of the soil organic matter producing greater quantities of essential elements in plant available mineral (inorganic) forms (Coleman et al. 1983, Klein et al. 1988, Bird et al. 2002, Burrows and Pfleger 2002, Rillig et al. 2002, Driver et al. 2005). The increased quantities of available essential elements provide for increased production of plant herbage biomass and increased livestock weight production (Manske 2008b).

This report includes a compilation of studies that evaluated the effects of management treatments on the quantity (weight or volume) of the Rhizosphere complex of organisms, active root segments, and adhered soil particles, and then evaluated the secondary effects that resulted from the rhizosphere quantities at various levels on the ecosystem biogeochemical processes. Each study will be treated separately.

Studies, Rhizosphere Organisms Affect on Grassland Ecosystems

A. 2006-2011 Study, Initial Effects from Twice-over Rotation Grazing

B. 1937-2011 Study, Seventy Five Years of Nongrazing

C. 1978-1990 Study, Effects of Prescribed Burning on Degraded Ecosystems

D. 1983-2018 Study, Evaluation of Biologically Effective Management

D1 1999-2000 Study, Finding Ectomycorrhizal Fungi in the Mixed Grass Prairie

D2 2002 Study, Determination of Rhizosphere Volume Around Grass Roots

D3 2006 Study, Determination of the Standard Reference Rhizosphere Weight

D4 1989-2018 Study, Availability of Soil Mineral Nitrogen

D5 2013-2018 Study, Soil Organic Matter (SOM) Affects Soil Quality

D6 2016-2018 Study, Evaluation of Soil Microbe Biomass and Activity

E. Summary of the Indispensable Rhizosphere Organisms

A. 2006-2011 Study, Initial Effects from Twice-over Rotation Grazing

The twice-over rotation grazing strategy was the biologically effective treatment used for the initial restoration of a degraded ecosystem. The degraded mixed grass prairie grassland comprised 1,988 acres (804.5 hectors) and was a working cattle ranch prior to 1993 managed by traditional seasonlong practices based on use as forage for livestock grazed at moderate to heavy rates maintaining low production native grassland ecosystems. Management by the USDI Bureau of Land Management (BLM), after the purchase of this land, was based on use for recreation and wildlife habitat and all cattle grazing was removed for 13 years between 1993 and 2005 resulting in severely degraded plant communities dominated with undesirable cool season domesticated grasses, primarily Kentucky bluegrass, smooth bromegrass, and crested wheatgrass (Manske 2012c).

This 6 year project was conducted during 2006 to 2011 in order to describe and evaluate development of the initial changes of the biological restoration of degraded intact grassland ecosystems through implementation of the biologically effective three pasture twice-over rotation management strategy compared to a control of nongrazing (Manske 2012c). A nongrazed control treatment was used to manage one native rangeland pasture (NR 4) during this study. The biologically effective concept was used to manage three native rangeland pastures (NR 1, 2, & 3) with a twice-over rotation system grazed for 4.5 months from 1 June to 15 October (137 days) with commercial crossbred cattle grazed at a mean 78% of the potential 176 AUE beef cows with a total combined weight on 1 June of 175,533 pounds stocked at 1.92 ac/AUM (Manske 2012c).

Procedure

Permanent sample plots organized in a paired-plot design of grazed and ungrazed treatments with a 16' X 32' (4.88 m X 9.75 m) stock panel exclosures preventing livestock access to the ungrazed plots was established on silty ecological sites of each pasture. Rhizosphere biomass was collected during three periods per growing season on the grazed and nongrazed treatments by three replicated soil cores (7.6 cm X 10.2 cm) using a humane soil beastie catcher (Manske and Urban 2012a). 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 and reported in kg/m^3. Soil mineral nitrogen, nitrate and ammonium, was sampled monthly (May to October) on the grazed and nongrazed treatments of the silty ecological sites by two replicated soil cores collected in incremental depths to 24 inches using a Veihmeyer soil tube with each sample air dried. Analysis of soil core samples for available mineral nitrogen (NO_3, NH_4) was conducted by the North Dakota State University Soil Testing Laboratory using wet chemistry methods. Aboveground herbage biomass was collected monthly (May to October) by the standard clipping method (Cook and Stubbendieck 1986) sorted in the field into domesticated grasses, cool season grasses, warm season grasses, upland sedges, forbs, standing dead, and litter and oven dried. Plant species basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986) and sorted into domesticated grasses, cool season grasses, warm season grasses, upland sedges, forbs, and litter.

Interpretation of treatment effects on plant community characteristics assumes only minor differences in the ecosystem status on the grazed treatment and nongrazed treatment at the time of the paired-plot exclosure constuction on each silty ecological reference site.

Results

Long-term perennial plant growing season precipitation (April to October) in the region near Richardton, ND, was 14.79 inches. Growing season precipitation during the first three years had a mean of 10.54 inches (71.26% of LTM). During the next three years, growing season presipitation had a mean of 14.07 inches (95.13% of LTM) (table 3).

The rhizosphere weights on the nongrazed and grazed treatments responded dissimilarly to the different treatments. During years 1 to 5, the small changes in rhizosphere weight on the nongrazed pasture at a mean of 5.7 kg/m^2 per year appeared to be related to the small changes in growing season precipitation at a mean of 1.00 inch (2.54 cm) per year. During year 6, there was a 28% increase in growing season precipitation at 3.72 inches (9.45 cm) per year and the rhizosphere weight on the nongrazed pasture increased 50% to 130.56 kg/m^3 (figure 1 and table 4).

The rhizosphere weights on the grazed pastures did not change during years 1 and 2 and they were not significantly different from the rhizosphere weights on the nongrazed pasture (table 4). The rhizosphere weights increased 33% during the third year on the grazed pastures and continued to increase at a mean rate of 30.5 kg/m^3 per year from year 3 to year 6, reaching a mean weight of 214.3 kg/m^3, which was 64.2% greater than the year 6 rhizosphere weight on the nongrazed pasture (figure 1 and table 4). The increase in rhizosphere weights during years three to six on the grazed pastures appeared to be related to increases in carbon energy exudates released from grass lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage following partial defoliation by grazing graminvores that removed 25% to 33% of the aboveground tiller material.

The partial defoliation of vegetative lead tillers resulting from the twice-over grazing treatment progressively decreased the rates of leaf senescence during the first two years and slowly increased the photosynthetic rates causing greater quantities of carbon to be fixed that became available for elevated grass growth and for exudation into the rhizosphere. During year 3, the increased quantities of exudated short chain carbon energy caused the rhizosphere weight on the grazed pastures to increase 73.5% greater than the weight of the rhizosphere on the nongrazed pasture. This greater rhizosphere weight and microorganism activity, resulted in mineralization of greater quantities of nitrogen and other essential elements from soil organic matter, which in turn, permitted greater grass growth and increased vegetative reproduction by tillering.

Mineral nitrogen available at low quantities below the threshold of 100 lbs/ac (112 kg/ha) is the major cause for less than potential levels of grass herbage production and calf weight gains and is a primary factor for ecosystem degradation (Manske 1999). The quantity of available mineral nitrogen is dependent on the biomass and activity levels of the microorganisms in the rhizosphere. The mean rhizosphere weight reached during year 6 on the nongrazed treatment was 130.56 kg/m^3 (figure 1 and table 4) which was only 32.1% of the standard reference rhizosphere weight of 406.44 kg/m^3. The quantity of available mineral nitrogen during the growing season was low on the nongrazed treatment (table 5). Nitrate and ammonium at the 0 to 12 inch depths peaked during May and was at decreased quantities the remainder of the growing season. The total quantity of available mineral nitrogen at the 0 to 24 inch depths peaked during July because both nitrate and ammonium levels peaked during July at the 12 to 24 inch depth. The quantity of available nitrate and ammonium remained relatively high at the 12-24 inch depth during June to September indicating very little grass root growth and activity at that soil depth (table 5).

The mean rhizosphere weight reached during year 6 on the grazed pastures was 214.34 kg/m^3 (figure 1 and table 4) which was 52.7% of the standard reference rhizosphere weight of 406.44 kg/m^3. The total quantity of available mineral nitrogen at the 0 to 24 inch depths peaked during May at 99.35 lbs/ac which was just a little shy of the threshold quantity of 100 lbs/ac (table 6). The values of available mineral nitrate and ammonium at each incremental depth from 0 to 24 inches were lower during the growing season months June to October than the peak values during May indicated robust grass root growth and activity at each incremental depth from 0 to 24 inches during all of the growing season months June to October (table 6). A rhizosphere weight of just over 50% of the standard reference rhizosphere weight on the twice-over rotation grazed pastures was able to mineralize nearly 100 lbs/ac of total available mineral nitrogen.

Native grass herbage biomass on the nongrazed pasture increased 59.6% and basal cover increased 33.3% during 6 years (tables 7 and 8). From year 1 to year 6, native grass herbage biomass production increased 175.2% and basal cover increased 153.3% on the grazed pastures (tables 9 and 10). During 6 years on the nongrazed pasture, domesticated grass herbage biomass increased 27.3% and basal cover increased 24.3% (tables 7 and 8). Domesticated grasses on the grazed pastures decreased herbage biomass 28.2% during year 5 but during year 6 herbage biomass increased 32.1% because of the reduced stocking rate. Basal cover of domesticated grasses on the grazed pastures increased 43.3% (tables 9 and 10). The increase in herbage biomass and basal cover of native grasses and domesticated grasses on the nongrazed treatment from year 3 to year 6 was primarily the increase in precipitation. The increase in domesticated grass herbage biomass and basal cover on the grazed pastures was the increase in precipitation and the decrease in stocking pressure. The huge increase in native grass herbage biomass and basal cover on the grazed pastures was caused by the great increase in available mineral nitrogen mineralized by the increased biomass of rhizosphere organisms.

The biologically effective twice-over rotation grazing treatment coordinated partial defoliation by grazing graminivores with phenological growth stages of grass plants which provided the biological requirements of all the above and belowground components of the grassland ecosystem activating the biogeochemcial processes performed by the rhizosphere organisms and the physiological mechanisms within the grass plants. After six growing seasons, the rhizosphere weight had increased 175% which was 53% of the long-term standard reference weight of 406.4 kg/m^3, and the plant community composition of native grass herbage biomass increased 99% and basal cover increased 69%. Neither the weight of the rhizosphere nor the composition of the plant community had been fully restored in 6 years. However, the necessary biogeochemical processes and physiological mechanisms had been activated in order for the ecosystem restoration to continue if the protocol for the twice-over rotation strategy is followed at a stocking rate of 80% to 100% of the assessed level (Manske 2012c)

Discussion

The mixed grass prairie ecosystems on the study area degraded because the previous management with no grazing was designed for an intended "use" that 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 regressive degrees less than potential level each growing season that the rangeland was managed with the traditional concept that assumes one use can be substituted for another 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 physiological mechanisms within grass plants diminished, the ecosystem biogeochemical processes declined, and the competitiveness of grass plant resource uptake deteriorated (Manske 2011b).

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 essential 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 of no grazing greatly reduced the quantity of short carbon chain energy exuded from the grass roots into the rhizosphere; the low amount of simple carbon compounds from leakage was not enough to sustain an adequate rhizosphere biomass. The small biomass of rhizosphere organisms only could 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, 2011b). 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 in availability 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 2011b).

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 have regressed and 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.

Table 3. 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	169.56	1.76	4.06	2.07	0.96	1.35	17.15
% of LTM	114.86	6809.44	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

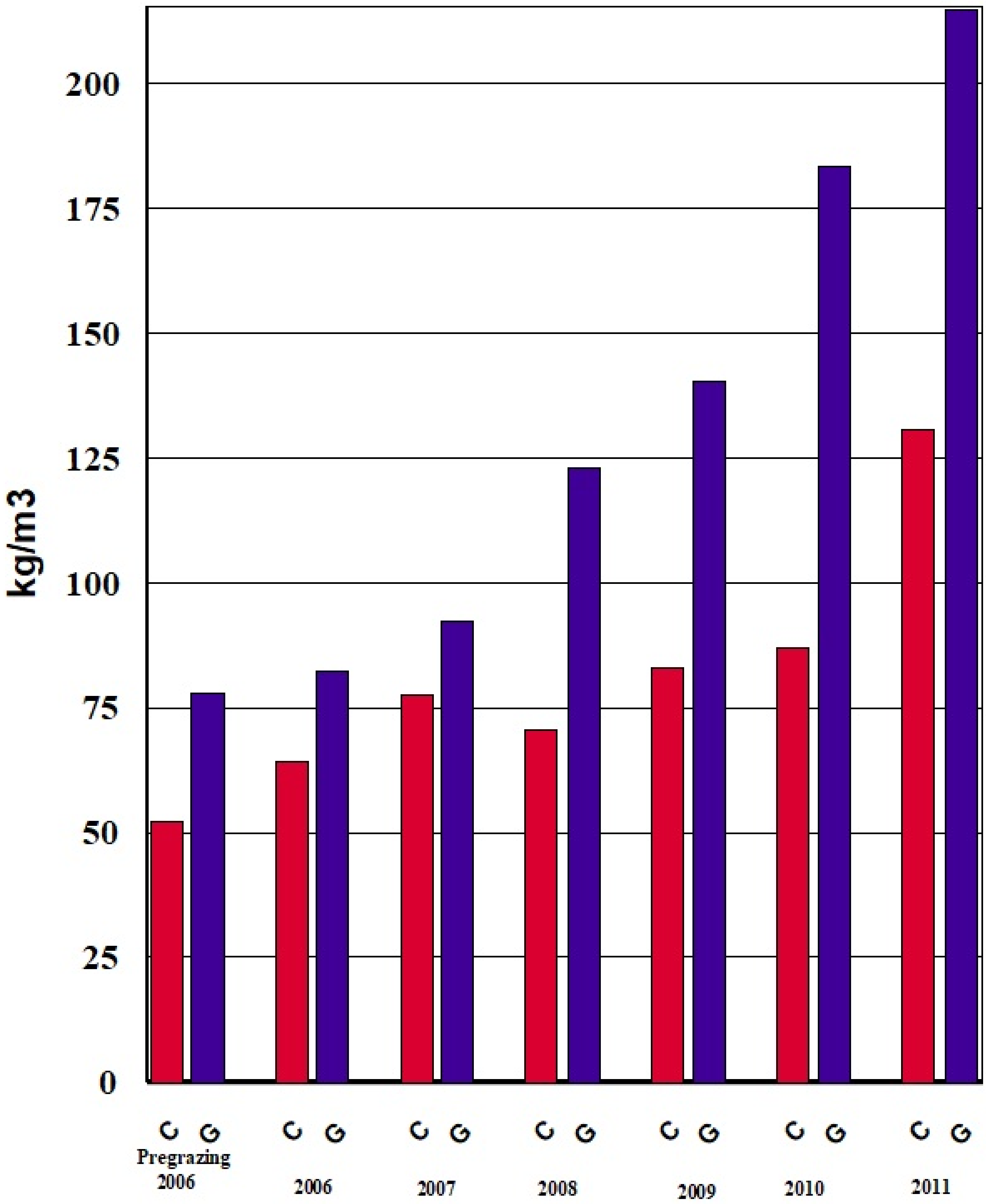

Figure 1. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Table 4. Rhizosphere weight (kg/m^3) for the nongrazed 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 ($P<0.05$).

Table 5. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac in incremental depths to 24 inches during growing season months on silty ecological sites of the nongrazed control, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6	13.25	13.00	8.75	6.50	5.25	7.50
6-12	9.75	6.75	6.00	5.00	4.25	4.25
12-24	7.69	10.00	19.00	11.00	4.00	4.00
0-24	30.69	29.75	33.75	22.50	13.50	15.75
NH_4 ammonium						
0-6	19.99	11.83	16.24	12.40	13.79	13.63
6-12	12.32	11.18	12.24	11.26	10.85	12.16
12-24	8.24	13.14	16.16	12.07	12.40	3.65
0-24	40.55	36.15	44.64	35.73	37.04	29.44
$NO_3 + NH_4$						
0-6	33.24	24.83	24.99	18.90	19.04	21.13
6-12	22.07	17.93	18.24	16.26	15.10	16.41
12-24	15.93	23.14	35.16	23.07	16.40	7.65
0-24	71.24	65.90	78.39	58.23	50.54	45.19

Table 6. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac in incremental depths to 24 inches during growing season months on silty ecological sites of the twice-over rotation grazed treatment, 2013-2014.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6	29.63	10.75	7.63	15.75	9.63	7.75
6-12	11.38	4.88	4.88	4.38	4.25	4.63
12-24	9.50	6.00	5.00	8.00	5.50	4.00
0-24	50.50	21.63	17.51	28.13	19.38	16.38
NH_4 ammonium						
0-6	20.21	14.44	14.77	16.88	19.00	14.81
6-12	14.20	10.32	13.96	15.46	12.57	12.52
12-24	14.45	11.67	14.44	11.99	13.30	3.88
0-24	48.85	36.42	43.17	44.33	44.87	31.21
$NO_3 + NH_4$						
0-6	49.83	25.19	22.39	32.63	28.62	22.56
6-12	25.57	15.20	18.83	19.84	16.82	17.15
12-24	23.95	17.67	19.44	19.99	18.80	7.88
0-24	99.35	58.06	60.66	72.46	64.24	47.59

Table 7. Mean herbage biomass (lbs/ac) for nongrazed silty native rangeland sites, 2006-2011.

Pastures NG Biotype	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	1833.85	1791.31	1320.16	1779.62	1468.69	2333.98
Native Grasses	132.32	236.81	142.46	304.91	283.71	211.22
Upland Sedges	25.91	22.27	20.29	49.44	30.48	11.82
Forbs	128.75	75.97	27.02	116.81	238.65	185.43
Standing Dead	1381.12	708.48	928.70	499.32	432.54	1229.02
Litter	2452.03	2131.29	2521.86	1946.39	1476.03	3178.78

Table 8. Basal cover (%) for nongrazed silty native rangeland sites, 2006-2011.

Pastures NG Biotype	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	12.35	19.95	11.20	15.30	23.60	15.35
Native Grasses	0.90	3.10	3.95	1.25	1.90	1.20
Upland Sedges	2.00	2.20	1.90	2.35	1.75	1.05
Forbs	0.80	0.30	0.10	0.10	1.15	0.20
Litter	83.95	74.45	82.85	81.00	71.60	82.20

Table 9. Mean herbage biomass (lbs/ac) for grazed silty native rangeland sites, 2006-2011.

Pastures TOR Biotype	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	954.70	1156.08	310.77	547.59	685.72	1261.24
Native Grasses	206.09	342.40	211.74	444.27	346.76	567.07
Upland Sedges	287.58	264.50	266.99	382.80	334.68	245.17
Forbs	122.28	77.06	35.17	94.50	357.87	100.11
Standing Dead	853.06	491.99	420.37	107.40	363.68	509.77
Litter	1479.24	1030.31	1114.80	610.79	473.94	898.17

Table 10. Basal cover (%) for grazed silty native rangeland sites, 2006-2011.

Pastures TOR Biotype	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Domesticated	4.80	5.35	4.08	6.20	6.88	6.88
Native Grasses	2.55	8.66	6.81	7.61	7.66	6.46
Upland Sedges	7.75	10.83	10.75	11.05	12.70	9.55
Forbs	0.45	0.43	0.20	0.45	3.05	0.50
Litter	84.43	74.75	78.18	74.10	69.73	76.63

B. 1937-2011 Study, Seventy Five Years of Nongrazing

The human population of western North Dakota greatly increased during 1898 to 1915 primarily because of the Homestead Act of 1862 transferred title for 160 acres (64.8 hectors) of surveyed public domain land from the US Government to private citizens. However, during the late 1920's and early 1930's economic depression, severe drought conditions, and low agricultural commodity prices created extreme hardships for homesteaders. The Land Utilization Project and resettlement plan of 1935 permitted the US Government to repurchase 1,104,789 acres (405,000 hectors) of submarginal homestead land in North Dakota (Hibbard 1965, Carstensen 1968, Manske 1994b, 2008a) for three designated specific purposes: for grazing use, for recreation use, and for wildlife use on three different identified land areas. The Bankhead-Jones Farm Tenant Act of 1937 provided for the implementation of followup conservation and utilization programs and development of improved practices of management of the repurchased grasslands. The USDA Agriculture Resettlement Administration authorized the establishment of experimental rangeland management laboratory areas by North Dakota Agricultural Experiment Station on the Little Missouri River Badlands (Whitman 1953). In 1936, Dr. Warren C. Whitman established four two-way rangeland reference areas that included a livestock exclosure and a similar area exposed to livestock grazing on sandy, shallow, silty, and overflow ecological sites (Hanson and Whitman 1938) and initiated the study to evaluate the effects to rangeland ecosystems caused by grazing and nongrazing.

This ongoing long-term project monitors changes in rhizosphere biomass, plant root biomass, soil mineral nitrogen, herbage biomass production, and plant species composition. During the growing season of 2011, the effects from long-term nongrazing after 75 years was compared to the effects from moderately stocked, 7 to 8 month from 1 May through 31 December, seasonlong grazing treatments, with the grazing season shortened because of inclement weather conditions during most years (Manske 2013).

Procedure

Rhizosphere biomass was collected on the grazed and nongrazed treatments of each ecological site by three replicated soil cores (7.6 cm X 10.2 cm) using a humane soil beastie catcher (Manske and Urban 2012a). 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 and reported in kg/m^3. Belowground plant root biomass was collected on the grazed and nongrazed treatments of each ecological site by two replicated soil cores 7.6 cm (3 in) in diameter and 10.2 cm (4 in) in depth. Root material was separated from soil in a water bath assisted with gentle manual agitation, placed in labeled paper bags of known weight, oven dried at 140° F (60° C), and weighed. Soil mineral nitrogen, nitrate and ammonium, was sampled on the grazed and nongrazed treatments of each ecological site by three replicated soil cores collected using a Veihmeyer soil tube and frozen. Analysis of soil core samples for available mineral nitrogen (NO_3, NH_4) was conducted by the North Dakota State University Soil Testing Laboratory using wet chemistry methods. Changes in vegetation composition over time were described using the ‘range condition index’. Range condition index is the percent similarity of the percent composition of the dry weights of major plant species and categories of minor species on a current ecological site compared to the hypothetically determined standards of the percent composition of the dry weights of the major and minor species for that same plant community at its best biological potential. Index values of 80% and greater are considered to be similar. Index values greater than 50% are degrees of similarity. Index values of less than 50% are degrees of dissimilarity. And index values of 20% and less are considered to be dissimilar. Aboveground herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986) sorted in the field into domesticated grasses, cool season grasses, warm season grasses, upland sedges, forbs, standing dead, and litter, and oven dried. Plant species basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986) and sorted into domesticated grasses, cool season grasses, warm season grasses, upland sedges, forbs, and litter. Density of forbs was determined by counting individual stems of each forb species rooted inside twenty five 0.1m^2 quadrats. Density of shrubs were collected by counting individual plants of each shrub species rooted inside twenty five 1.0 m^2 quadrats. A species present list of shrubs, cacti, and trees were also completed. These procedures adequately represented the shrub component of the grazed plant communities, however, because of the great extent and high number of woody species growing inside the exclosures, these methods greatly undersampled the woody species growing inside the exclosures.

Surface area of the woody infected shrub and tree map units and the nonwoody grass map units were determined in acres as digital data in ArcGIS by occular assessment of USDA National Agriculture Imagery Program 2009 orthoimages as displayed by Google Earth was conducted by the Dickinson State University Department of Agriculture and Technical Studies (Manske 2013).

Results

The standard reference rhizosphere weight of 406.4 kg/m^3 was recorded on silty ecological sites managed long-term (24 years) with a twice-over rotation grazing strategy. All of the measured rhizosphere weights on the grazed seasonlong and nongrazed treatments from the four ecological sites of this study were lower than 45% of the standard reference rhizosphere weight after 75 years of management indicating that all of these treatments were detrimental, but not lethal, to rhizosphere organisms (figure 2 and table 11). The rhizosphere weights on the nongrazed treatments of the sandy and overflow ecological sites were substantially lower than the rhizosphere weights on the grazed seasonlong treatments indicating that the nongrazed treatments were more detrimental to rhizosphere organisms than the grazed seasonlong treatments. The lowest rhizosphere weight on a seasonlong treatment was on the silty ecological site which was similar to the rhizosphere weight on the nongrazed treatment of the silty ecological site indicating that the long-term stocking rate on the grazed seasonlong treatment was a little heavier or the grazing season was longer by starting earlier and coming off later than the grazed seasonlong treatments of the sandy and overflow ecological sites and that the heavily grazed treatment and nongrazed treatment of the silty ecological site had similar detrimental effects on the rhizosphere organisms. The rhizosphere weight on the grazed seasonlong treatment of the shallow ecological site was lower than the rhizosphere weight on the nongrazed treatment indicating that a relatively recent change in the grazing management was more detrimental to the rhizosphere organisms than the previous grazing treatment and the nongrazed treatment of the shallow ecological site (figure 2 and table 11).

The weight of the grass roots on the nongrazed treatments of all four ecological sites were substantially lower than the weight of the grass roots on the grazed seasonlong treatments. When grazing graminivores are removed from native rangeland ecosystems, the stimulation effects from partial defoliation of aboveground leaf material stops, causing the ecosystem biogeochemical processes and physiological mechanisms within grass plants to decrease resulting in great reductions in above and belowground grass biomass growth, hence, extremely low root weights on the nongrazed treatments (table 12).

Available soil mineral nitrogen is the major limiting factor of herbage growth on native rangeland ecosystems (Wight and Black 1979). Deficiencies in mineral nitrogen limit herbage production more often than water in temperate grasslands (Tilman 1990). A minimum rate of mineralization that supplies 100 lbs/ac (112 kg/ha) of mineral nitrogen is required to sustain herbage production at biological potential levels on rangelands (Wight and Black 1972). Wight and Black (1972, 1979) determined that the processes associated with precipitation (water) use efficiency in grass plants were not fully activated unless 100 lbs/ac of mineral nitrogen was available. When less than 100 lbs/ac of available mineral nitrogen occurred in rangeland ecosystems, the weight of herbage produced per inch of precipitation received was reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on rangeland ecosystems that had 100 lbs/ac of mineral nitrogen or greater (Wight and Black 1979). Manske (2010a, b) found two major plant mechanisms that performed the compensatory physiological processes within grass plants and the processes for vegetative reproduction by tillering could not be activated when less than 100 lbs/ac of mineral nitrogen was available and were fully activated when greater than 100 lbs/ac of mineral nitrogen was available.

The quantity of organic nitrogen mineralized in an ecosystem is dependent on the biomass and activity levels of the microorganisms in the rhizosphere. The quantity of mineral nitrogen immobilized in an ecosystem is dependent on the rate of plant growth. The quantity of available soil mineral nitrogen, nitrate and ammonium, varies with changes in rhizosphere microorganism biomass and the changes in plant growth rate during the growing season (Whitman 1975). The quantity of available mineral nitrogen, nitrate and ammonium, on the grazed seasonlong and nongrazed treatments were at deficiency levels on all four ecological sites (table 13). Available mineral nitrogen was lower on the nongrazed treatments than on the grazed treatments of the sandy, silty, and overflow ecological sites as a result of the lower rhizosphere weight. Available mineral nitrogen was lower on the grazed seasonlong treatment than on the nongrazed treatment of the shallow ecological site as a result of a recent detrimental change in grazing management (table 13).

The ecosystem deterioration of the aboveground vegetation was severe on the nongrazed treatments of the four ecological sites. The native graminoids greatly decreased. The decrease in herbage biomass ranged from 32% to 96% with a mean of 58.7% for the cool season grasses, from 63% to 99% with a mean of 86.5% for the warm season grasses, and from 24% to 95% with a mean of 55.6% for the upland sedges (tables 14, 15, 16, 17, and 22). The decrease in basal cover ranged from 49% to 100% with a mean of 80.2% for the cool season grasses, from 85% to 100% with a mean of 92.7% for the warm season grasses, and from an increase of 2% to decrease of 92% with a mean decrease of 33.5% for the upland sedges (tables 14, 15, 16, 17, and 22).

As a result of the ecosystem deterioration on the nongrazed treatments, the domesticated grasses, mainly Kentucky bluegrass, increased, with increases of herbage biomass ranging from 100% to 1,647% with a mean of 481.3% and with increases of basal cover from a decrease of 33% to an increase of 3,700% with a mean increase of 56.2% (tables 14, 15, 16, 17, and 22). The herbage biomass of the standing dead greatly increased that ranged from a small decrease of 35% to an increase of 10,434% with a mean increase of 2,772.7% (tables 14, 15, 16, 17, and 22). The herbage biomass of the litter increased ranging from 131% to 811% with a mean of 470.1% and litter basal cover increase ranged from 19% to 32% with a mean of 23.2% (tables 14, 15, 16, 17, and 22).

The change in forbs, as one category, was negative and positive as a result of the ecosystem deterioration of the nongrazed treatments. The changes in herbage biomass ranged from a decrease of 58% to an increase of 72% with a mean of a 4.0% increase. The changes in basal cover ranged from a decrease of 59% to an increase of 167% with a mean of 4.9% increase (tables 14, 15, 16, 17, and 22). The number of forb species present greatly decreased on the nongrazed treatments of all four ecological sites with a mean decrease of 53.1% (table 22).

The similarity index of range condition on the four grazed ecological reference areas ranged from 52.7% to 68.4% with a mean of 58.6%, low good condition, indicating that the composition of the current grazed plant communities were slightly similar to the composition of the hypothetical standard historical plant communities (table 18). The composition of the aboveground vegetation on the grazed shallow ecological site has not yet deteriorated to the extent of the deterioration of the belowground components. The similarity index of range condition on the four nongrazed ecological reference areas ranged from 19.1% to 36.8% with a mean of 28.0%, low fair condition, indicating that the composition of the current nongrazed plant communities were nearly dissimilar, with the nongrazed areas on the shallow and silty ecological sites dissimilar, to the composition of the hypothetical standard historical plant communities (table 18). The current plant communities on the nongrazed areas had degraded from the hypothetical standard plant communities 51.3% greater than the amount of degradation that had ocurred on the current plant communities on the grazed areas after 75 years (table 22).

With forbs separated into three categories of late stage, mid stage, and early stage of succession, the results of the ecosystem deterioration of the nongrazed treatments on the four ecological sites showed different effects. The late stage forb density decreased on the sandy, shallow, and overflow sites and increased on the silty site (table 19) with a mean decrease of 52.0% (table 22). The mid stage forb density increased on the sandy and shallow sites and decreased on the silty and overflow sites (table 19) with a mean increase of 35.9% (table 22). The early stage forb density decreased on the sandy, shallow and silty sites and increased on the overflow site (table 19) with a mean decrease of 60.2% (table 22). The late stage forbs decreased as a result of the reduced ecosystem biogeochemical processes. The early stage forbs decreased as a result of the reduced amount of sunlight reaching the soil level because of the increased biomass of standing dead and litter. The mid stage forbs increased because they were able to survive without the benefits of the ecosystem biogeochemical processes.

The greatest visual impact occurring as a result of the ecosystem deterioration of the nongrazed treatment on all four ecological sites was the huge increase of woody shrubs, cacti, and trees with an increase of 254.2% in species present (tables 20 and 22) and an increase of 62.4% of the land area occupied by woody plants (tables 21 and 22).

The nongrazed and grazed seasonlong areas had not been burned for at least 75 years and most likely for a great deal of time longer. Both the nongrazed and grazed treatments had a lack of fire for a long time, however, the woody plant infestation only occurred on the nongrazed treatments. The basal cover of native graminoids was 24.2% on the grazed treatments and 7.0% on the nongrazed treatments for a reduction of 71.1%. This reduction in basal cover along with the reduction in above and belowground plant biomass has caused a great reduction in competitiveness in the native graminoids. The belowground resources of nutrients and soil water that had previously been used by the healthy robust graminoids, but no longer consumed by the smaller, less vigorous degraded graminoids, are taken up by the encroaching woody species resulting in proportional increases in woody plant biomass production (Kochy and Wilson 2000). As woody stem density increased, the competition shifted to primarily the aboveground resources of light; under these different degraded conditions, woody species have the advantage and the graminoids are strongly suppressed (Kochy and Wilson 2000). The great increase of woody plants into grassland ecosystems has not been the result of fire suppression. The increased woody plant infestation has been caused by the greatly reduced competitiveness of the graminoids and the degradation of the biogeochemical processes in the grass plant communities caused by the removal of grazing by large graminivores.

Grassland ecosystem deterioration occurs first in the belowground components. The rhizosphere microbes decrease in biomass, the biogeochemical processes cycle less essential elements and the quantity of available mineral nitrogen decreases. Consequently, the aboveground components deteriorate. The native grasses and forbs decrease in herbage biomass and density followed by increases in herbaceous invader species and then by increases in woody invader species.

Discussion

Removal of cattle grazing does not promote development of stable climax plant communities and does not preserve prairie grasslands in perpetuity. Grassland communities deprived of large grazing graminivores decline steadily into unhealthy disfunctional ecosystems with severe reductions of native grasses, considerable decreases of desirable forbs, enormous increases of introduced domesticated grasses, remarkable increases of woody shrubs and trees, and excessive increases of standing dead and litter.

Grass plants have four major mechanisms: compensatory physiological mechanisms, efficient water use mechanisms, mechanisms for vegetative reproduction by tillering, and competitive resource uptake mechanism that permit growth and functionality. The ecosystem has numerous biogeochemical processes performed by achlorophyllous soil microorganisms that provide available essential elements needed for growth of all ecosystem organisms and these important microbes depend on grass plants to fix their energy. The grazing graminivores activate plant mechanisms and ecosystem processes with partial defoliation and depend on nutritious forage produced by the grass plants. All of there complex mechanisms and processes are interconnected and interdependent that require an adequate supply of essential elements with a threshold of mineral nitrogen to be available at 100 lbs/ac and require activation by removal of 25% to 33% of lead tiller material at phenological growth stages between the three and a half new leaf stage and the flower stage by large grazing graminivores. If any of the numerous processes are not functioning at potential level, the ecosystem does not function at potential level. Management of grassland ecosystem must meet the biological and physiological requirements of all the biotic components and also stimulate the biogeochemical processes that cycle and recycle the abiotic components.

The key to control of undesirable woody shrub and tree and herbaceous plant encroachment into grassland ecosystems is to regain the competitive advantage of the native grasses by restoration of the mechanisms and processes in the prairie ecosystem that results from proper biologically effective partial defoliation coordinated with grass phenological growth stages by large grazing graminivores which are an indispensable biotic component of grasslands.

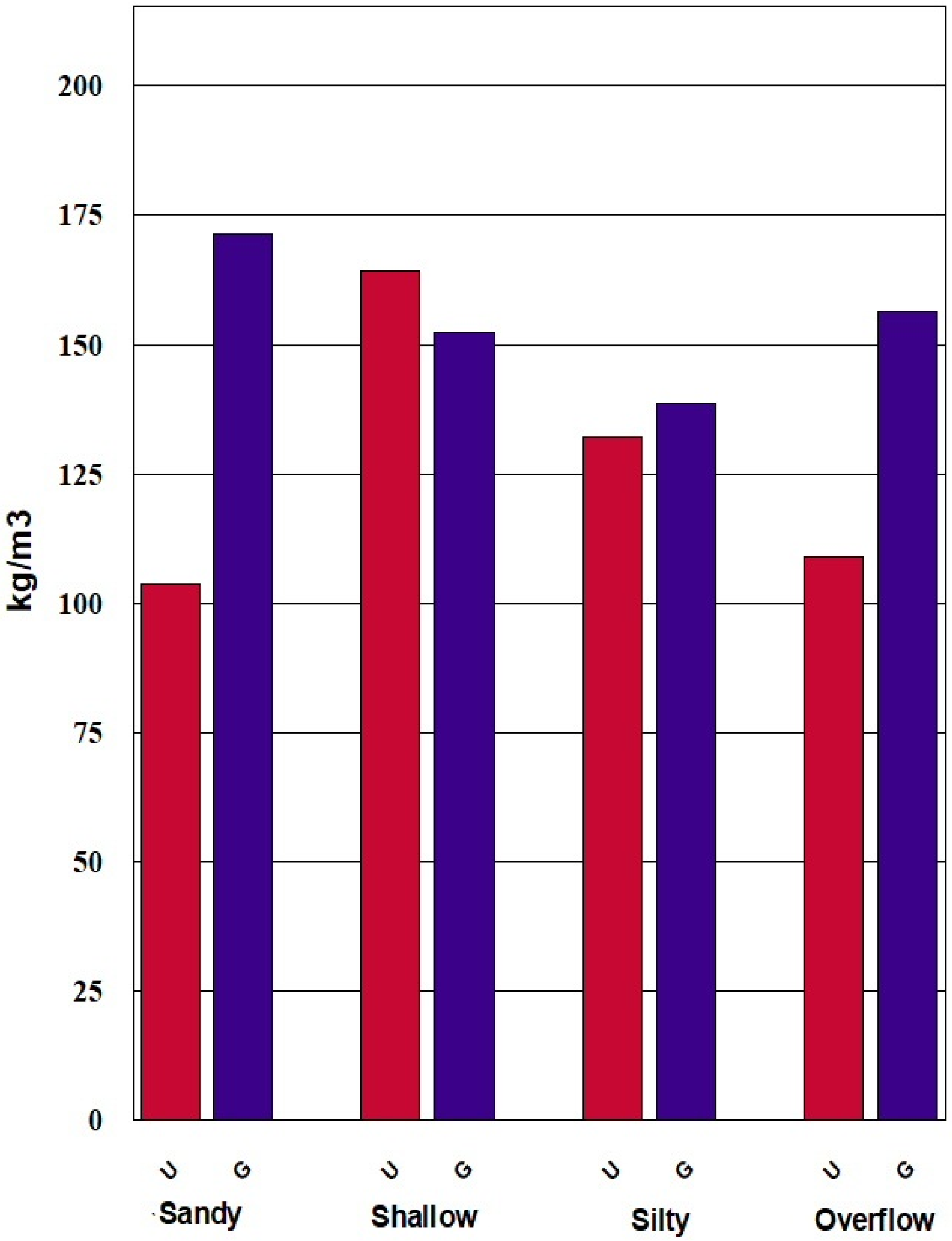

Figure 2. Rhizosphere weight (kg/m3) for the ungrazed exclosure (red) and grazed area (blue) on the ecological site reference areas in the Little Missouri River Badlands, 1936-2011.

Table 11. Rhizosphere biomass (kg/m^3) for native rangeland on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

	Rhizosphere Biomass (kg/m^3)		
Ecological Sites	Grazed	Exclosure	% Difference
Sandy	171.01	103.74	-39.34
Shallow	152.59	163.88	7.40
Silty	138.63	132.08	-4.72
Overflow	156.55	109.21	-30.24

Table 12. Belowground biomass (kg/m^3) of roots for native rangeland on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

	Belowground Biomass (kg/m^3)		
Ecological Sites Component	Grazed	Exclosure	% Difference
Sandy			
Root	32.48	14.35	-55.82
Shallow			
Root	34.53	26.87	-22.18
Silty			
Root	24.82	16.73	-32.72
Overflow			
Root	14.35	11.12	-22.51

Table 13. Soil available mineral nitrogen (nitrate NO_3 and ammonium NH_4) for native rangeland on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

	Available Mineral Nitrogen (lbs/ac)		
Ecological Sites Mineral Nitrogen	Grazed	Exclosure	% Difference
Sandy			
Nitrate NO_3	6.33	7.33	15.80
Ammonium NH_4	25.19	16.19	-35.73
$NO_3 + NH_4$	31.52	23.52	-25.38
Shallow			
Nitrate NO_3	6.00	6.00	0.00
Ammonium NH_4	27.12	35.26	30.01
$NO_3 + NH_4$	33.12	41.26	24.58
Silty			
Nitrate NO_3	11.00	10.00	-9.09
Ammonium NH_4	35.62	32.02	-10.11
$NO_3 + NH_4$	46.62	42.02	-9.87
Overflow			
Nitrate NO_3	9.67	14.33	48.19
Ammonium NH_4	48.56	36.70	-24.42
$NO_3 + NH_4$	58.23	51.03	-12.36

Table 14. Herbage biomass (lbs/ac) and Basal cover (%) for native rangeland on the sandy reference area after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Sandy Ecological Site		Herbage Biomass (lbs/ac)			Basal Cover %	
Biotype	Grazed	Exclosure	% Difference	Grazed	Exclosure	% Difference
Domesticated	0.00	1158.89	100.00	0.15	5.70	3700.00
Cool Season	803.51	239.77	-70.16	3.25	1.65	-49.23
Warm Season	468.84	102.04	-78.24	14.25	2.20	-84.56
Upland Sedges	505.23	203.38	-59.75	11.60	7.05	-39.22
Forbs	147.72	156.99	6.28	0.85	0.35	-58.82
Standing Dead	353.23	230.49	-34.75	-	-	-
Litter	104.90	791.38	654.41	69.85	83.05	18.90

Table 15. Herbage biomass (lbs/ac) and Basal cover (%) for native rangeland on the shallow reference area after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Shallow Ecological Site		Herbage Biomass (lbs/ac)			Basal Cover %	
Biotype	Grazed	Exclosure	% Difference	Grazed	Exclosure	% Difference
Domesticated	0.00	1299.47	100.00	0.00	5.80	100.00
Cool Season	583.01	22.84	-96.08	7.95	0.90	-88.68
Warm Season	215.51	3.57	-98.34	13.90	0.25	-98.20
Upland Sedges	287.58	154.85	-46.15	10.30	10.50	1.94
Forbs	183.40	316.12	72.37	2.70	1.55	-42.59
Standing Dead	3.57	376.07	10434.17	-	-	-
Litter	70.65	643.67	811.07	62.65	75.90	21.15

Table 16. Herbage biomass (lbs/ac) and Basal cover (%) for native rangeland on the silty reference area after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Silty Ecological Site		Herbage Biomass (lbs/ac)			Basal Cover %	
Biotype	Grazed	Exclosure	% Difference	Grazed	Exclosure	% Difference
Domesticated	692.91	1427.91	106.07	17.45	11.65	-33.24
Cool Season	506.66	101.33	-80.00	3.25	0.00	-100.00
Warm Season	201.24	0.71	-99.65	2.75	0.00	-100.00
Upland Sedges	149.14	113.46	-23.93	5.70	1.15	-79.82
Forbs	124.88	149.86	20.00	0.90	2.40	166.67
Standing Dead	112.04	494.52	341.38	-	-	-
Litter	563.03	2162.21	284.03	64.25	84.80	31.98

Table 17. Herbage biomass (lbs/ac) and Basal cover (%) for native rangeland on the overflow reference area after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Overflow Ecological Site		Herbage Biomass (lbs/ac)			Basal Cover %	
Biotype	Grazed	Exclosure	% Difference	Grazed	Exclosure	% Difference
Domesticated	12.13	211.94	1647.24	0.20	4.65	2225.00
Cool Season	1559.93	1061.84	-31.93	18.60	4.00	-78.49
Warm Season	57.80	21.41	-62.96	4.50	0.15	-96.67
Upland Sedges	135.58	7.14	-94.73	0.60	0.05	-91.67
Forbs	239.06	99.90	-58.21	1.20	0.65	-45.83
Standing Dead	300.43	1351.56	349.88	-	-	-
Litter	648.66	1497.85	130.91	74.90	90.50	20.83

Table 18. Similarity index of range condition for the grazed areas and nongrazed areas on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Ecological Reference Area	Similarity Index of Range Condition		
	Grazed Area	Nongrazed Area	% Difference
Sandy	59.8	36.8	-38.4
	Low Good	Low Fair	
Shallow	68.4	20.1	-70.6
	Good	Poor	
Silty	53.6	19.1	-64.4
	Low Good	Poor	
Overflow	52.7	36.1	-31.6
	Low Good	Low Fair	
Mean of Four	58.6	28.0	-51.3
	Low Good	Low Fair	

Table 19. Forb density (#/0.10 m^2) related to succession stage for native rangeland on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

Ecological Sites Treatments	Late Stage Forbs	Mid Stage Forbs	Early Stage Forbs	Total Live Forbs
Sandy				
Grazed	5.28	0.20	0.36	5.88
Exclosure	1.28	2.16	0.04	3.48
% Difference	-75.76	980.00	-88.89	-40.82
Shallow				
Grazed	22.52	0.36	0.88	23.80
Exclosure	3.92	5.88	0.08	9.88
% Difference	-82.59	1533.33	-90.91	-58.49
Silty				
Grazed	5.12	3.20	2.16	10.48
Exclosure	12.56	0.24	0.00	12.80
% Difference	145.31	-92.50	-100.00	22.14
Overflow				
Grazed	6.48	3.92	1.52	11.92
Exclosure	1.16	2.16	1.84	5.16
% Difference	-82.10	-44.90	21.05	-56.71

Table 20. Shrubs, cacti, and trees present on the reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

	Sandy		Shallow		Silty		Overflow	
Woody Plants	Graze	Exclosure	Grazed	Exclosure	Grazed	Exclosure	Grazed	Exclosure
Silver sagebrush				X		X	X	X
Common juniper						X		
Creeping juniper						X		
Chokecherry		X		X		X		
Skunkbush		X		X		X		
Prairie wild rose	X	X	X	X	X	X		
Buffalo berry						X		
Western snowberry		X	X	X	X	X	X	X
Great Plains yucca		X				X		
Ball cactus	X	X						
Prickly pear	X	X				X		
Green ash				X		X		X
Rocky Mtn juniper		X		X		X		
Plains cottonwood								X
Number Present	3	8	2	7	2	12	2	4

Table 21. Acreage and percent land area occupied by nonwoody grass and woody shrub and tree infested plant communities on the four reference areas after 75 years in the Little Missouri River Badlands, ND, 1936-2011.

	Exclosure	Major Plant Communities			
	Total Area	Nonwoody Plants		Woody Plants	
Ecological Sites	acres	acres	%	acres	%
Sandy	6.27	2.93	46.67	3.34	53.33
Shallow	4.90	2.15	43.90	2.75	56.10
Silty	14.10	6.52	46.23	7.58	53.77
Overflow	2.90	0.40	13.80	2.50	86.20

Determined by Arc GIS mapping procedures.

Table 22. Percent difference in plant community characteristics on the nongrazed exclosure area compared to the grazed area after 75 years on the four reference areas in the Little Missouri River Badlands, ND, 1936-2011.

Biotype	Sandy Ecological Sites	Shallow Ecological Sites	Silty Ecological Sites	Overflow Ecological Sites	Mean of Four Ecological Sites
Herbage Biomass					
Domesticated	100.00	100.00	106.07	1647.24	481.3
Cool Season	-70.16	-96.08	-80.00	-31.93	-58.7
Warm Season	-78.24	-98.34	-99.65	-62.96	-86.5
Upland Sedges	-59.75	-46.15	-23.93	-94.73	-55.6
Forbs	6.28	72.37	20.00	-58.21	4.0
Standing Dead	-34.75	10434.17	341.38	349.88	2772.7
Litter	654.41	811.07	284.03	130.91	470.1
Basal Cover					
Domesticated	3700.00	100.00	-33.24	2225.00	56.2
Cool Season	-49.23	-88.68	-100.00	-78.49	-80.2
Warm Season	-84.56	-98.20	-100.00	-96.67	-92.7
Upland Sedges	-39.22	1.94	-79.82	-91.67	-33.5
Forbs	-58.82	-42.59	166.67	-45.83	4.9
Litter	18.90	21.15	31.98	20.83	23.2
Forb Density					
Late Stage	-75.76	-82.59	145.31	-82.10	-52.0
Mid Stage	980.00	1533.33	-92.50	-44.90	35.9
Early Stage	-88.89	-90.91	-100.00	21.05	-60.2
Total Live	-40.82	-58.49	22.14	-56.71	-39.8
Species Present	-53.9	-50.0	-56.3	-52.9	-53.1
Shrub Density					
Species Present	166.7	250.0	500.0	100.0	254.2
% Woody Area	53.33	56.10	53.77	86.20	62.35
Range Condition					
Similarity Index	-38.4	-70.6	-64.4	-31.6	-51.3
Rank	Low Fair	Poor	Poor	Low Fair	Low Fair

C. 1978-1990 Study, Effects of Prescribed Burning on Degraded Ecosystems

Many grassland ecologists have accepted the observational concept that the occurrence of fire was the force that prevented intrusion of shrubs and trees into grasslands. However, the processes of how fire prevents woody species encroachment into prairie has not been clearly explained. Total plant kill caused by fire occurs only to species of evergreen conifers and one deciduous shrub, big sagebrush. All other deciduous trees and shrubs are temporarily set back with partial damage or top kill of aerial stems by fire. Deciduous woody species recover and replace the damaged stems with sprout growth from vegetative buds (Manske 2014d). A study of the effects from repeated prescribed burning once to four times during a thirteen year period on degraded mixed grass prairie was conducted.

The US Government repurchased 26,904 acres (10,896 ha) of submarginal homestead land in Burke and Mountrail counties of North Dakota as permitted by the Land Utilization Project and resettlement plan of 1935 for wildlife use which later became the USDI Fish and Wildlife Service, Lostwood National Wildlife Refuge (Manske 1994).

Management of Lostwood Refuge has been based on the concept of preserving wildlife habitat with little or no disturbance (idle). All grazing on the refuge was stopped between 1935 and 1940. After 1940, all of the upland acreage (about 59% of the refuge), except the areas of wetlands (20%) and the land designated as wilderness (21%), was grazed periodically using deferred seasonlong management. Some parcels were grazed only one time while other parcels were grazed as many as 22 times in the 35 year period between 1940 and 1975. Also, during this time period, a parcel of about 7,000 acre (2,833 ha) (26% of the refuge) was grazed annually with deferred seasonlong management for 4.5 to 5.0 months at low to moderate stocking rates during July through November (Smith 1988).

About 23% of the refuge land area had previously been used as cropland by homesteaders. About 35% of the cropland acres were allowed to revegetate through natural secondary succession as “go back” land. The remaining cropland parcels were managed as cropland to provide winter food for resident wildlife. In the mid 1950's, these existing cropland acres were seeded with domesticated cool season grasses, primarily smooth bromegrass and crested wheatgrass (Smith 1988).

The changes in vegetation cover was described from a series of black and white aerial photographs by Smith (1988) and summarized here. The Lostwood Wildlife Refuge increased in shrub cover from about 5% during the mid 1930's to greater than 50% in 1979. This change, however, did not occur at a uniform rate. The shrub composition in the plant community did not change much during the first 20 years. A substantial increase in shrub cover occurred between 1953 and 1969, and then, between 1969 and 1979, the western snowberry colonies expanded rapidly and invaded extensive areas of degraded grassland. As a result, over half of the refuge upland was transformed into shrubland (Smith 1988). Few trees existed on the refuge during the 1930's and 1940's, but by 1985, there were over 540 expanding aspen groves covering about 475 acres (192 ha) interspersed across the landscape located at the edges of seasonal wetlands. Over 55%, about 300 of the aspen groves had completely occupied previous wetland basins (Smith 1997).

Domesticated cool season grasses had greatly increased over five decades of vegetation change. Kentucky bluegrass was the dominant grass associated with the western snowberry colonies. Large portions of the western snowberry colonies were extremely dense and had no herbaceous understory. Decadent centers of old western snowberry colonies had been reinvaded by smooth bromegrass, quackgrass (Smith 1985a), and Canada thistle (Smith 1985b).

Remnant native grasses and forbs were present in low quantities with greatly suppressed distribution as a result of the previous long-term management concepts of no disturbance and deferred seasonlong grazing. The deferred-type management that delays grazing until after the flowering stage of grasses is known to decrease grass tiller density and grass plant competitiveness (Sarvis 1941, Manske et al. 1988).

The historical records for the region indicate that the local homesteaders had been able to suppress all fires from sometime in the late 1800's and indirectly implied that the land area that became the wildlife refuge had not been burned by wildfire or prescribed fire during the 80 year period prior to 1978 (Smith 1985b).

In 1978, refuge manager Karen Smith initiated an every-other-year prescribed burning strategy. This burning regime was designed to reduce the invading western snowberry and the exotic domesticated cool season grasses with the intent to renovate the prairie ecosystem. Annual burns were not possible because of insufficient production of plant biomass for fuel (Smith 1985a). The refuge, except the wilderness area, was subdivided into prescribed burn management units that used trails or mowed swaths as fire breaks. Several parcels of the refuge were designated to receive no burning treatments for use as reference control areas. The prescibed burn management units received 1, 2, 3, or 4 repeated every-other-year burns during the 13 year period between 1978 and 1990. During the growing season of 1990, Manske (1992) evaluated the effects of every-other-year prescribed burning after thirteen years of treatments. This report is a summary of that study.

Procedure

Field data were collected along permanent landscape transects that included the plant communities on the summit, shoulder, back, foot, and toe slopes from 15 prescribed burn management units with an average size of 530.5 acres (214.85 ha) and 6 control management units of no burning with an average size of 436.8 acres (176.90 ha) (Manske 1992).

Endomycorrhizal fungal infection in roots was evaluated for blue grama, western wheatgrass, smooth bromegrass, and western snowberry. Three replicated soil cores were collected for each species from nearly level loam soils along the permanent landscape transects of each control and prescribed burn treatment using a golf cup cutter. In the laboratory, root samples were prepared using procedures described by Phillips and Hayman (1970) and modified by Kormanik and McGraw (1982). Percent fungal infection was assessed using a nonsystematic modification of the grid-intersect method (Giovannetti and Mosse 1980), with presence or absence (P/A) of fungal structures recorded for 100 intersected root segments viewed through a Nikon microscope.

Changes in soil microorganism activity were monitored by changes in the quantity of soil inorganic (mineral) nitrogen. Soil mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), was determined from five replicated soil core samples 0-6 inches in depth, collected from nearly level loam soil sites along the permanent landscape transects using the one inch Veihmeyer soil tube during mid June and mid August from the no burn control treatment and each burn treatment with 1 to 4 burns with each sample air dried. 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 using wet chemistry methods (Manske 1992).

Gravimetric soil water data (Cook and Stubbendieck 1986) were collected on both the summit slopes and foot slopes of each landscape transect during June, July, and August using a Veihmeyer soil tube to 24 inches in depth.

Aboveground herbage biomass was collected during peak growth in mid July by the standard clipping method (Cook and Stubbendieck 1986), sorted in the field into grasses, sedges, forbs, shrubs, and standing dead, and oven dried. Plant species composition was determined during mid July to mid August by the plant shoot cover method (% shoot frequency) (Cook and Stubbendieck 1986), with one hundred 0.1 m^2 quadrats per landscape transect.

Results

Annual precipitation during the 13 year (1978-1990) study period averaged 15.36 inches (390.14 mm) (93.10% of LTM). Precipitation during the perennial plant growing season (April through October) averaged 12.35 inches (313.69 mm) (89.48% of LTM). A wet growing season occurred during 1984. Normal growing season precipitation occurred during 8 years. Water deficiencies occurred during 1979, 1983, 1987, and 1988 causing water stress in perennial plants resulting in restricted herbage biomass production (Manske 2007a). The inches of soil water during the growing season to 24 inches in depth on the summit slope (table 23) and the lower slope (table 24) were not significantly different among the no burn control treatment and the 1 to 4 every-other-year burn treatments (Manske 2007a).

Percent endomycorrhizal fungi infection of root segments of four major plant species, blue grama, western wheatgrass, smooth bromegrass, and western snowberry, was determined (table 25). There was no significant difference in percent fungal infection of each plant species root segments among the no burn control treatments and the 1 to 4 every-other-year burn treatments (Manske 2007a).

A problem developed with the technique in determining percent infection. All of the roots of each species collected were included in the evaluation samples. Endomycorrhizal fungi, however, do not colonize the entire root. Fungal colonization occurs at the portions of current years' roots that are biologically active. Previous years' roots, mature root portions, and young growing root portions do not host fungal structures. Identification of biologically active root portions from mature root portions is difficult with the naked eye or low power hand lens. Therefore, the reported (table 25) percent fungal infection of root segments is primarily a factor of the proportion of biologically active root portions in relation to the amount of mature and young root portions included in the sample. Basically, the less than 100% fungal infection of the blue grama, western wheatgrass, and western snowberry root samples in table 25 should be considered to indicate the percentage of biologically active root portions within the root sample. The percent fungal infection in the root segments of blue grama, western wheatgrass, and western snowberry were not changed significantly by the no burn or the number of repeated every-other-year prescribed burn treatments. The quantity of endomycorrhizal fungal colonization in plant roots was not stimulated by the prescribed burning treatments.

The percent fungal infection data for the smooth bromegrass root segments were not applicable to standard evaluation. The smooth bromegrass root samples contained a small amount of young and mature root portions, with most of the samples appearing to consist of biologically active root portions. The large proportion of seemingly ideal biologically active root segments had effectually no fungal infection. The observed fungal infections were restricted to the root hairs. Under a microscope, the root hairs had a swollen bulb-like part where the hair attached to the root which was the site for the fungal infection. Smooth bromegrass had relatively low fungal infection in the root hairs (table 25).

The escaped smooth bromegrass plants present on the no burn and burn treatments at the Lostwood Wildlife Refuge had long aggressive rhizomes and were nonmycorrhizal which would fit the description of the Southern Type. The Southern Type smooth bromegrass germ plasm originated from the Hungarian Plains and France that have both basal leaves and stem leaves, strongly rhizomatous producing mostly rhizome tillers resulting in sod forming plants with high seed viability, strong seedling vigor, that grows rapidly early in the growing season for a short period producing greater peak aboveground herbage biomass (Manske 2017).

The quantities of available mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), were unusually low on the no burn controls and the 1 to 4 every-other-year burn treatments (table 26). Most of the nitrogen in grassland soils is in the organic form and unavailable for direct use by plants. The soil organic nitrogen must be mineralized by rhizosphere microorganisms to provide plant usable mineral nitrogen (Ingham et al. 1985). Grassland ecosystems with low biomass of rhizosphere organisms mineralize low quantities of organic nitrogen into mineral nitrogen (Coleman et al. 1983). The low quantities of mineral nitrogen (NO_3 & NH_4) available in the soils of the 1 to 4 repeated every-other-year prescribed burn treatments were not significantly changed from the low quantities of mineral nitrogen available in the soils of the control no burn treatments (Manske 2007a). The rhizosphere microorganism biomass and activity levels were not stimulated by any of the prescribed burn treatments, and the quantity of organic nitrogen mineralized into mineral nitrogen was not increased by any of the prescribed burn treatments. The low available mineral nitrogen was a primary cause for low herbage production and the reason annual burns were not possible.

The low total peak live herbage production was not different after one, two, three, and four repeated prescribed burns compared to the low live biomass produced on the no burn treatments (table 27). However, the composition of the aboveground biomass did change.

The shrub biomass contribution was 47.5% on the no burn treatments, shrub biomass decreased 83.1% after one burn and decreased 95.1% after four burns. Shrub biomass contribution was only 3.0% after four burns (table 27).

The forb biomass increased 78.0% after one burn and the contribution to total aboveground biomass was 139.7% greater than that on the no burn treatments. After two and three burns, the weedy forbs decreased and the prairie perennial forbs improved. Forb biomass increased 4.4% after four burns and the biomass contribution to the total biomass was 35.3% greater after four burns than that on the no burn treatments. The contribution of forbs to the total biomass was 15.0% on the no burn treatments and increased to 20.3% after four burns (table 27).

Upland sedge biomass increased 61.6% after one burn and decreased 35.1% after four burns. The contribution of upland sedges to the total biomass was 13.2% on the no burn treatments and decreased to 11.1% after four burns (table 27).

Native grass biomass decreased 24.7% after one burn and increased 109.3% after four burns. The contribution of native grass to the total biomass was 24.2% on the no burn treatments and increased to 65.6% after four burns (table 27) as a result of reduced shading and increased sunlight.

Shoot frequency of native grasses increased as a result of repeated burning. The average increase in shoot frequency was 79.6% after one, two, and three burns and increased 94.7% after four burns (table 28). However, the actual basal cover of native grasses was not well developed after four burns (Manske 2007a) because the physiological mechanisms were not activated within the grass plants.

Upland sedge shoot frequency increased an average of 58.4% after repeated burns (table 28).

Shoot frequency of the domesticated grasses decreased an average of 49.4% after one, two, and three burns and decreased 65.1% after four burns (table 28). Four burns were required to temporarily reduce domesticated grasses significantly (Manske 2007a). Shoot frequency of Kentucky bluegrass decreased an average of 36.2% after one, two, three, and four burns. Shoot frequency of Quackgrass decreased an average of 84.0% after one and two burns and decreased an average of 90.9% after three and four burns. Shoot frequency of Smooth bromegrass decreased an average of 90.0% after one and two burns and decreased an average of 96.7% after three and four burns.

Shoot frequency of perennial prairie forbs increased 39.3% after one burn (table 28) then shoot frequency averaged 7.5% above the shoot frequency on the no burn treatments after two, three, and four burns. Early stage forbs and weedy forbs shoot frequency increased 8.2% after one burn, decreased an average of 7.5% after two and three burns, and decreased 50.9% after four burns (table 28). Four burns were required to reduce early stage and weedy forbs significantly (Manske 2007a).

Shoot frequency of shrubs decreased 36.4% after one burn, decreased an average of 46.1% after two and three burns, and decreased 58.2% after four burns (table 28). Four burns were required to reduce shrubs significantly (Manske 2007a).

Shoot frequency of western snowberry decreased 68.3% after one burn, decreased 40.0% after two burns, decreased 67.1% after three burns, and decreased 58.4% after four burns. The greatest reduction in shoot frequency occurred from early spring (mid-late April) burns. The repeated burns of 2 to 4 times caused no significant reduction in shoot frequency after one burn, however, the aboveground biomass produced by shrubs was greatly reduced after the third and fourth burns (Manske 2007a). Western snowberry reproduced vegetatively from buds on rhizomes and crowns. Removal of all or most of the aboveground shoots with fire does not stop the vegetative reproductive processes. Burning cannot remove deciduous shrubs and trees that produce vegetative sprouts from grassland communities.

Burning treatments did not increase water infiltration or soil water holding capacity. Burning treatments did not increase endomycorrhizal fungal colonization. Burning treatments did not increase rhizosphere microbe biomass and activity levels. Burning treatments did not increase mineralization of organic nitrogen into inorganic nitrogen. Burning treatments did not increase total herbage biomass production. Burning treatments did not restore functionality to the degraded grassland ecosystem.

Burning treatments did modify the composition of the aboveground plant community. The composition of introduced cool season grasses, early stage and weedy forbs, and shrub aerial stems decreased temporarily after four repeated prescribed burns. However, the fundamental problems of weak nutrient resource uptake, reduced water use efficiency, nonfunctional compensatory physiological mechanisms and vegetative reproduction by tillering remained within the plants and diminished biogeochemical processes remained in the degraded ecosystems following repeated burning treatments. None of the biological, physiological, or asexual mechanisms within grass plants and none of the rhizosphere microbes or the biogeochemical processes they perform were activated by burning treatments. Burning treatments did not and cannot improve grassland ecosystems biologically or ecologically.

Discussion

The existence of a woody plant component in a grassland is not an ecologically beneficial relationship as woody plants and grasses are adversarial inhibitive competitors. They compete for sunlight, mineral nitrogen, other essential elements, and soil water.

Seedlings of trees, shrubs, weedy forbs, and introduced grasses cannot become established in grasslands containing healthy grasses with full nutrient resource uptake competitiveness (Peltzer and Kochy 2001). Fire in grasslands cannot prevent the invasion of, or cause the removal of, shrubs, and trees that are able to reproduce by vegetative secondary suckers (Wright and Bailey 1982, Manske 2006a, b). Almost all deciduous woody plants reproduce vegetatively, except big sagebrush (Artemisia tridentata) (Manske 2014d). Intrusive seedlings can only become established in a grassland after the ecosystem has been degraded by poor management practices.

Burning of grasslands exacerbates ecosystem degradation. When the losses of essential elements are greater than the quantity of captured essential elements, the result is degradation of the grassland ecosystem (McGill and Cole 1981). Almost all of the essential elements in the aboveground herbage are volatilized when a grassland is burned, with no active processes to recapture the lost essential elements. When burning occurs during dry soil periods, some of the belowground essential elements are also lost (Russelle 1992). Burning grasslands does not restore degraded ecosystems. Degraded grasslands continue to have the same fundamental problems following the repeated prescribed burning regime, and when the burning sequence stops, the undesirable replacement plants return to dominate the communities.

The presence of fire does not prove that grasslands need or are caused by fire (Heady 1975). Burning does not improve grassland ecosystems biologically or ecologically and fire cannot replace the contribution that partial defoliation by grazing graminivores achieves in managing healthy and productive grassland ecosystems.

Table 23. Inches of soil water by sample depth from summit slope position with deep loam soils after 13 years of no burns and 1 to 4 every-other-year burns on the Lostwood Wildlife Refuge, ND, 1978-1990.

Summit Slope Treatment	Soil Depth Inches	Jun	Jul	Aug
No Burns	0-6	-	0.88	0.68
	6-12	-	0.65	0.53
	12-24	-	1.48	1.10
	0-24	-	3.01a	2.31b
1 Burn	0-6	1.53	1.07	0.84
	6-12	1.00	0.75	0.67
	12-24	2.43	1.66	1.28
	0-24	4.97	3.48a	2.79b
2 Burns	0-6	-	0.91	0.67
	6-12	-	0.64	0.56
	12-24	-	1.37	0.95
	0-24	-	2.92a	2.18b
3 Burns	0-6	1.09	0.74	0.74
	6-12	0.63	0.59	0.54
	12-24	1.43	0.99	1.02
	0-24	3.15	2.32a	2.30b
4 Burns	0-6	0.82	0.89	0.72
	6-12	0.65	0.76	0.51
	12-24	1.15	1.10	1.13
	0-24	2.62	2.75a	2.36b

Data from Manske 1992.

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

Table 24. Inches of soil water by sample depth from lower slope position with deep loam soils after 13 years of no burns and 1 to 4 every-other-year burns on the Lostwood Wildlife Refuge, ND, 1978-1990.

Lower Slope Treatment	Soil Depth Inches	Jun	Jul	Aug
No Burns	0-6	1.46	1.12	0.73
	6-12	0.84	0.72	0.61
	12-24	1.84	1.64	1.26
	0-24	4.14	3.48c	2.60d
1 Burn	0-6	1.55	1.02	0.83
	6-12	1.18	0.96	0.66
	12-24	1.94	1.50	1.53
	0-24	4.67	3.48c	3.02d
2 Burns	0-6	2.00	1.06	0.67
	6-12	1.13	0.91	0.55
	12-24	1.54	1.27	1.27
	0-24	4.67	3.24c	2.49d
3 Burns	0-6	-	0.87	0.97
	6-12	-	0.68	0.56
	12-24	-	1.33	1.18
	0-24	-	2.88c	2.71d
4 Burns	0-6	1.77	1.00	0.74
	6-12	1.22	1.25	0.65
	12-24	2.54	2.19	1.88
	0-24	5.53	4.44c	3.27d

Data from Manske 1992.

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

Table 25. Mycorrhizal fungal infection of plant roots on the silty ecological sites after 13 years of no burns and 1 to 4 every-other-year burn treatments on the Lostwood Wildlife Refuge, ND, 1978-1990.

Biotype		No Burns 6 reps	1 Burn 4 reps	2 Burns 4 reps	3 Burns 4 reps	4 Burns 3 reps
Blue grama						
Fungi infection	(%)	78.8a	77.1a	84.9a	79.9a	73.5a
Western wheatgrass						
Fungi infection	(%)	65.7b	67.0b	61.3b	76.8b	63.8b
Smooth bromegrass						
Fungi infection	(%)	32.4c	41.3c	50.0c	31.4c	40.1c
Western snowberry						
Fungi infection	(%)	93.8d	84.7d	84.3d	85.2d	85.9d

Data from Manske 1992.
Means in the same row and followed by the same letter are not significantly different ($P<0.05$).

Table 26. Available mineral nitrogen (NO_3-N and NH_4-N) in lbs/ac-ft during June and August on the silty ecological sites after 13 years of no burns and 1 to 4 every-other-year burn treatment on the Lostwood Wildlife Refuge, ND, 1978-1990.

Mineral Nitrogen lbs/ac-ft	No Burns 6 reps	1 Burn 4 reps	2 Burns 4 reps	3 Burns 4 reps	4 Burns 3 reps
June					
NO_3-N	25.88	19.94	30.74	10.25	11.88
NH_4-N	17.85	21.63	13.57	8.58	15.11
Total N	43.73a	41.57a	44.31a	18.83a	26.99a
August					
NO_3-N	6.72	4.18	5.61	4.44	11.49
NH_4-N	11.94	17.29	11.49	12.86	11.23
Total N	18.66b	21.47b	17.10b	17.29b	22.71b

Data from Manske 1992.
Means in the same row and followed by the same letter are not significantly different ($P<0.05$).

Table 27. Herbage biomass (lbs/ac) by biotype categories in mid July after 13 years of no burns and 1 to 4 every-other-year burn treatments on the Lostwood Wildlife Refuge, ND, 1978-1990.

Biotype	No Burns 6 reps	1 Burn 4 reps	2 Burns 4 reps	3 Burns 4 reps	4 Burns 3 reps
Native Grass	411.61	310.12	762.75	512.87	861.51
Upland Sedge	224.56	362.93	74.34	238.58	145.81
Forbs	242.83	454.35	445.14	587.41	266.49
Shrubs	806.83	136.00	237.09	52.00	39.57
Total Live	1698.35a	1263.39a	1519.19a	1390.87a	913.66a
Standing Dead	817.43	390.19	226.81	223.36	252.06

Data from Manske 1992.

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

Table 28. Shoot frequency (%) of plant biotypes during July to August after 13 years of no burns and 1 to 4 every- other-year burn treatments on the Lostwood Wildlife Refuge, ND, 1978-1990.

Biotype		No Burns 6 reps	1 Burn 4 reps	2 Burns 4 reps	3 Burns 4 reps	4 Burns 3 reps
Domesticated	%	86.7	46.3	31.8	53.5	30.3
Cool Season	%	89.2	169.8	152.8	179.0	175.7
Warm Season	%	17.8	24.5	30.5	19.8	32.7
Upland Sedges	%	56.7	95.5	97.0	77.8	89.0
Late Stage Forbs	%	120.5	167.8	125.5	137.5	125.7
Early Stage Forbs	%	59.3	74.3	54.3	48.3	19.7
Weedy Forbs	%	12.3	8.8	13.0	6.5	8.0
Shrubs	%	111.7	71.0	58.5	62.0	46.7
Fringed Sage	%	13.8	9.5	13.0	23.3	14.3
Total Shoot Frequency		568.0	667.5	576.4	607.7	542.1

Data from Manske 1992.

D. 1983-2018 Study, Evaluation of Biologically Effective Management

A 36 year study evaluated characteristics of various management practices to determine the factors related to biologically effective management. A long-term nongrazed control treatment replicated two times, was used as a nondefoliation practice for managing native rangeland during this study. The traditional concept managed the land for its use as forage for livestock and was used to manage one native rangeland pasture, replicated two and three times during various periods, with a seasonlong system stocked with 7 cows/80 acres at 11.43 ac/AU and 2.60 ac/AUM for 4.5 months from 1 June to 15 October (137 days). The biologically effective concept managed the land as an ecosystem that considers the biological requirements of the grass plants, soil microbes, and the livestock and was used to manage three native rangeland pastures, replicated two times, with a twice-over rotation system stocked with 8 cows/80 acres at 10.22 ac/AU and 2.30 ac/AUM for 4.5 months from 1 June to 15 October (137 days).

Commercial cow-calf pairs grazed the native rangeland pastures through this study. During 1983 to 1994, commercial Angus-Hereford cows with Charolais sired calves were used. These cows were assigned to separate herd pools for each grazing treatment. During 1995 to 2012, commercial crossbred cattle were used on all grazing treatments. During 2013 to 2018, cows with variable ratios of breed combinations with mixed breed sired calves were used. Before spring turn out cow-calf pairs were sorted by cow age, and calf age, with 50% steers or bulls and heifers.

D1. 1999-2000 Study, Finding Ectomycorrhizal Fungi in the Mixed Grass Prairie

Livestock producers have typically observed changes in the soil structure and quality in their native rangeland pastures after three to five years of management with the twice-over rotation strategy. They notice that shovels are easily pushed into the soil, grass density thickens, grass rooting depth increases 12 to 24 inches deeper, and watershed harvest dams fail to fill because of a decrease in water runoff. These commonly observed changes in native rangeland soils had to have a cause.

These observations continued for many growing seasons with no definitive answer available. Until a McKenzie county, ND, rancher observed a huge difference in his predominately clayey soils that had changed from a rooting depth and water holding soil profile of 2 to 3 inches to an aggregated soil of 18 to 24 inches in depth after seven years of management with a twice-over rotation system. Hence, soil samples from his ranch were collected and taken for analysis by Soil Microbiologist TheCan Caesar-TonThat PhD at her laboratory at USDA Agricultural Research Service, Sidney, MT. She detected the presence of ectomycorrhizal fungi. During the field seasons of 1999 and 2000 replicated soil cores were collected from the sandy and silty ecological sites of pastures managed with the seasonlong and twice-over rotation grazing strategies of the 1983-2018 Study at the Dickinson Research Extension Center ranch located in Dunn County in western North Dakota. The soil samples were analyzed by Dr. Caesar-TonThat in Sidney, MT. The absorbance readings determined the presence of ectomycorrhizal fungi from the Basidiomycota phylum (previous taxon:Homobasidiomycetes class and Russuloid clade order) current taxon: Agaricomycetes class and Russulales order in both the sandy and silty soil cores from the twice-over rotation system but not in the soil cores from the seasonlong system (Manske 2007b).

The effects from the twice-over rotation strategy had enhanced the development of ectomycorrhizal fungi in the rhizosphere of mixed grass prairie grasses. Active ectomycorrhizal fungi form water-stable aggregates in soil that are water permeable but not water soluble by secreting large amounts of insoluble extracellular polysaccharides that have adhesive qualities (Caesar-TonThat et al. 2001b). Adhesive polysaccharides act as binding agents for soil particles, causing aggregation of soil (Caesar-TonThat 2002) that range from about the size of air rifle pellets to the size of large marbles. Increases in soil aggregation enlarges soil pore size and improves distribution and stabilization of soil particles. These improvements in soil quality cause increases in soil oxygenation, increases in water infiltration, and decreases in erodibility (Caesar-TonThat and Cochran 2000, Caesar-TonThat et al. 2001a, Caesar-TonThat et al. 2001b, Caesar-TonThat 2002, Manske and Caesar-TonThat 2003). Increased soil aggregation contributes to improvement of grassland ecosystem soil structure and quality increasing productivity.

ECTOMYCORRHIZAL FUNGI

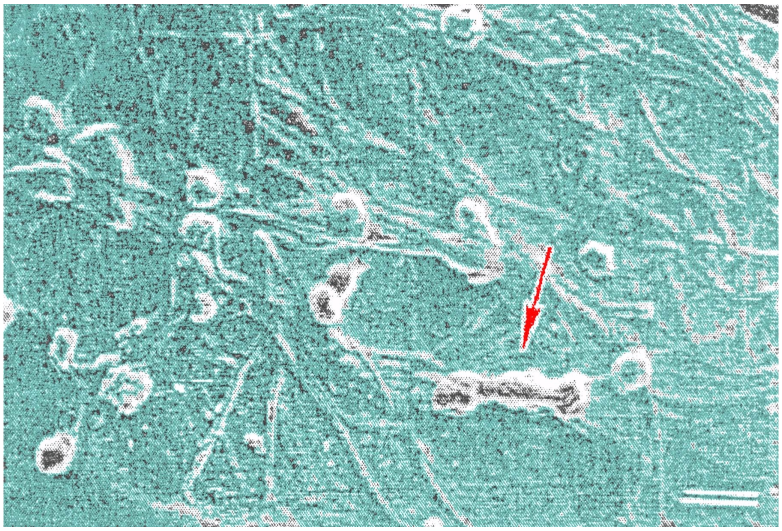

Photo from T.C. Caesar-TonThat

Ectomycorrhizal fungus with extracellular polysaccharides

D2. 2002 Study, Determination of Rhizosphere Volume Around Grass Roots.

The rhizosphere is the zone of bonded soil particles surrounding active perennial grass roots. The soil cylinder provides the living quarters for symbiotic microbes. The resident organisms are endomycorrhizal fungi, ectomycorrhizal fungi, bacteria, and protozoa and visiting organisms are nematodes, springtails, and mites. These rhizosphere organisms interact in a complex trophic web that is critical for nutrient flow in grassland ecosystems. The rhizosphere organisms are achlorophyllous and limited by access to energy. Healthy grass plants produce double the quantity of leaf biomass, capture and fix large amounts of carbon during photosynthesis, and produce carbohydrates in quantities greater than the amount needed for normal growth and maintenance. After the three and a half new leaf stage and before the flower stage, partial defoliation of grass tillers that removes 25% to 33% of the aboveground biomass by large grazing graminivores causes great quantities of the simple carbohydrates to be exudated through the roots into the rhizosphere. With this increase in available carbon compound energy in the rhizosphere, the biomass and activity of the microorganisms increase resulting in changes of the volume of the rhizosphere.

Measuring biomass of soil microbes is a perplexing difficulty. However, rhizosphere microbes reside in a bonded soil particle structure that changes in size and weight with increases or decreases in microorganism biomass and activity which can be measured.

Procedure

This one growing season project was conducted to evaluate rhizosphere volume from diameter and length measurements of each rhizosphere surrounding every western wheatgrass root contained within two replicated soil cores, 3 inches (7.62 cm) in diameter and 4 inches (10.16 cm) in depth, that were collected monthly from June to September and removed intact inside plastic PVC pipe that had been forced into soil of silty ecological sites managed for 20 years by three different treatments; a) long-term nongrazed control, b) traditional seasonlong grazed 4.5 months, and c) twice-over rotation strategy. The rhizosphere material, which included the rhizosphere organisms, the active plant roots extending from plant crown to tip, and the adhered soil particles, was separated from matrix soil by meticulous excavation with fine hand tools. Exposed rhizosphere segments 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 grass plant, including associated vegetative tillers, were measured with a vernier caliper and used to determine total rhizosphere volume per cubic meter of soil for each sample period of each of the three treatments (Gorder, Manske, and Stroh 2004).

Results

Precipitation during the perennial plant growing season (April through October) of 2002 was 18.85 inches (129.78% of LTM) and considered to be above average. September experienced water deficiency conditions.

Rhizosphere volume was not different among the three management treatments during the early season month of June and was not different between the nongrazed and seasonlong treatments during August and September (figure 3 and table 29). The twice-over sample pasture #1 was grazed during the stimulation period from early July to mid July followed by a remarkable increase in rhizosphere volume of 123.45% from the starting June volume. The rhizosphere volume of 6885 cm^3/m^3 on the twice-over management treatment was significantly greater than the volume of 2415 cm^3/m^3 on the nongrazed and the volume of 1883 cm^3/m^3 on the seasonlong treatments as mean of August and September (figure 3 and table 29).

Rhizosphere volume is a proxy measurement for soil microorganism biomass. The significant increase of rhizosphere volume on the twice-over treatment indicates that a significant increase in microorganism biomass and activity levels also occurred and would indicate increased rates of mineralization of organic nitrogen into mineral nitrogen. Greater quantities of available mineral nitrogen would support a greater population of grass tillers.

The total western wheatgrass tiller density/m^2 on the twice-over management treatment was significantly greater than that on the seasonlong treatment during August and September (table 30). During June, the total tiller density on the twice-over treatment was greater than those on both the nongrazed and seasonlong treatments. The tiller numbers present in June would include the second year lead tillers, the surviving previous fall initiated secondary vegetative tillers, and the current spring initiated secondary vegetative tillers. The twice-over management treatment is the only grazing treatment that stimulates a significant quantity of spring initiated secondary tillers (Manske 2014a, b).

Discussion

Production of grassland herbage and livestock weight performance at potential biological levels requires all of the primary grass plant mechanisms and the ecosystem biogeochemical processes to be functioning at potential levels. Elevation of the rhizosphere microorganism biomass is the initial objective in order for mineralization of nitrogen to occur at or above the threshold rate of 100 lbs/ac (112 kg/ha) which permits the primary grass mechanisms to be activated. Rhizosphere organisms are limited by access to energy in the form of short carbon chains. Soil microbes are achlorophyllous and cannot fix carbon energy and must depend on grass plants for their source of energy. Exudation of carbon energy can be released from grass lead tillers through the roots into the rhizosphere by removal of 25% to 33% of the aboveground leaf biomass by large grazing graminivores when the lead tillers are at vegetative phenological growth between the three and a half new leaf stage and the flower (anthesis) stage during early June to mid July which is the stimulation period (Manske 1999, 2011b, 2014c). Depending on the degree of degradation of the grassland ecosystem, three to five or more growing seasons are required to increase the rhizosphere microorganism biomass to levels capable of mineralization of 100 lbs/ac (112 kg/ha) or greater of available mineral nitrogen. Full activation of the primary internal grass plant mechanisms requires mineral nitrogen to be available at the threshold level or greater and requires the quantity of available carbon fixed through photosynthesis from 75% to 67% of the leaf area of predefoliated lead tillers before the flower stage and from 50% of the leaf area after the flower stage (Manske 2010a, b). The increased rhizosphere volume and microorganism biomass permits cycling greater quantities of the major and minor essential elements. With increased provisions of essential elements, grass tillers are able to synthesize greater quantities of carbohydrates, proteins, and nucleic acids and to accelerate growth rates of replacement leaves and shoots, increase photosynthetic capacity of remaining mature leaves, increase secondary tiller development from axillary buds, enhance competitiveness of nutrient resource uptake, and improve water use efficiency. The combination of increased ecosystem biogeochemical processes and improved functioning of the internal grass plant mechanisms results in increases in grass herbage production and increases in plant density (basal cover) of the desirable native grass species. This increase in available forage quantity and improved quality through the entire growing season results in improved livestock weight grains on less land area.

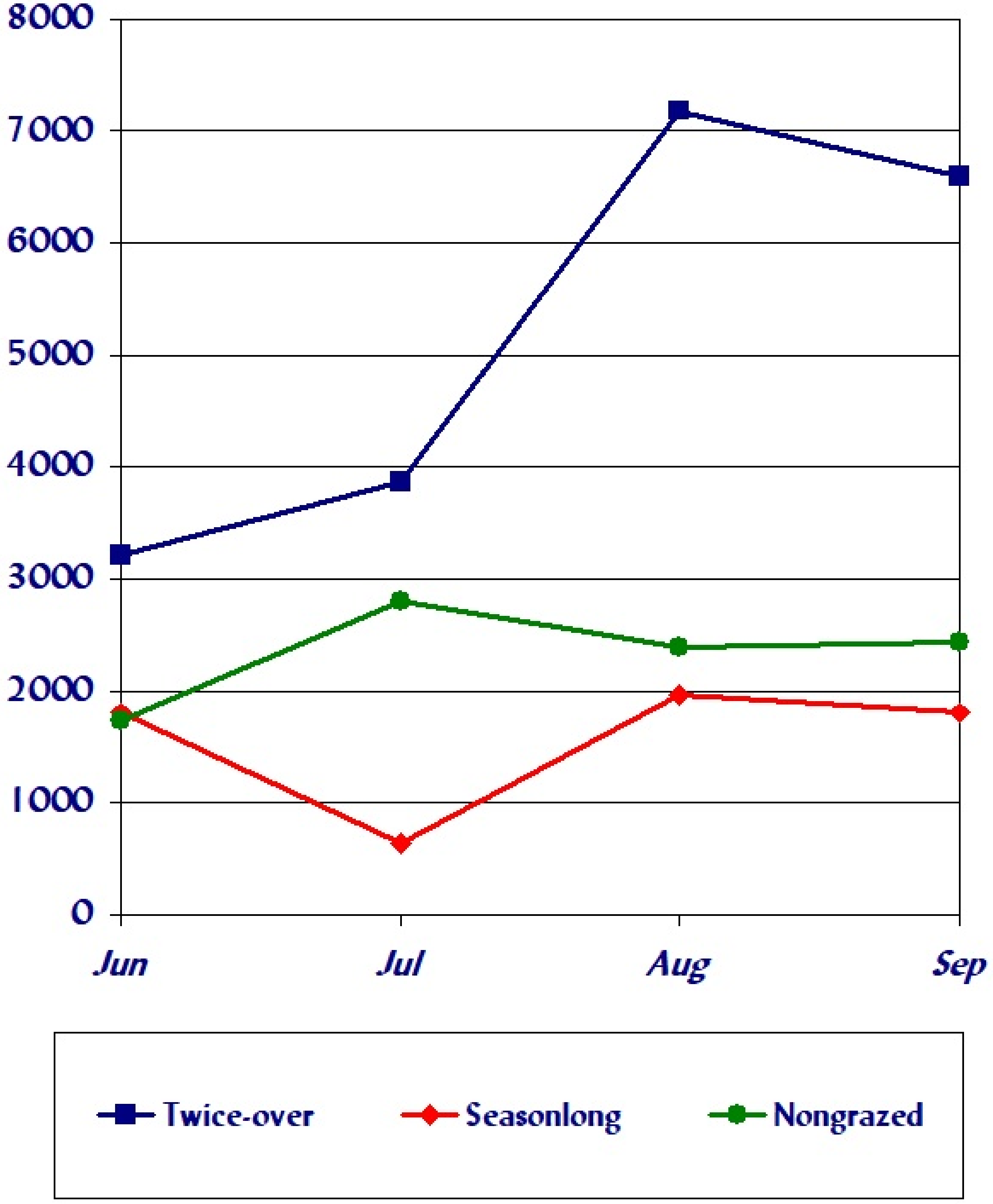

Figure 3. Rhizosphere volume (cm^3) per cubic meter of soil

Table 29. 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.

Table 30. Total tiller density of western wheatgrass per square meter on silty ecological sites, 2002.

Grazing Management	May	Jun	Jul	Aug	Sep	Oct
Nongrazed		548.20y	548.20x	877.12xy	1206.04x	
Seasonlong		548.20y	657.84x	767.48y	657.84y	
Twice-over		2412.09x	1206.04x	1973.53x	1425.32x	

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.

D3. 2006 Study, Determination of the Standard Reference Rhizosphere Weight

Evaluation of the initial effects of restoration of degraded prairie ecosystems with the twice-over rotation system would require collection of quantitative data showing changes in rhizosphere size for the 2006-2011 study. During the growing season of 2002, we perfected the technique to measure rhizosphere volume which was extremely effective at delineating differences among management treatments. However, measurement of rhizosphere volume of every root within a soil core required 8 to 10 hours of tedious labor plus calculations of total rhizosphere volume per soil core and per treatment required a great deal of additional time.

Measurement of rhizosphere weight consisted of placement of each rhizosphere into a container of known weight upon being revealed from the matrix soil and determining the total weight after all rhizospheres within a soil core had been exposed. This process required 2 to 3 hours of meticulous excavation with fine hand tools per soil core.

All of the rhizosphere weight values collected from degraded ecosystems would be at some quantity less than potential, which at that time was unknown. A small study was conducted during mid June 2006 to measure the possible maximum rhizosphere weight from silty ecological sites that had been managed long-term (24 years) by the twice-over rotation strategy.

Procedure

Rhizosphere biomass was collected on three replicated grazed pastures managed by the twice-over rotation system for 24 years since 1983 by three replicated soil cores from the silty ecological sites of each pasture using a humane soil beastie catcher (Manske and Urban 2012a). 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 and weighed.

Results

The resulting mean Standard Reference Rhizosphere Weight was 406.44 kg/m^3 recorded on silty ecological sites managed long-term (24 years) with a twice-over rotation grazing strategy.

D4. 1989-2018 Study, Availability of Soil Mineral Nitrogen

Nitrogen is an extremely important major essential element in grassland ecosystems. Deficiencies of available mineral nitrogen result in low herbage biomass production, deterioration of plant density and species composition, and reduced livestock weight performance. All rangeland soils managed with traditional grazing practices are deficient in mineral nitrogen (Wight and Black 1972, 1979). However, rangeland soils of the Northern Plains are not deficient in nitrogen. Most prairie soils contain 5 to 6 tons, with a range of 3 to 8 tons, of nitrogen per acre. Most of this nitrogen is immobilized in the soil as organic nitrogen and is not available for plant use. Soil organic nitrogen must be converted into mineral nitrogen through mineralization by rhizosphere microorganisms. Pastures with deficiencies in available mineral nitrogen is actually a deficiency in rhizosphere microorganism biomass which is strictly a management caused problem.

The quantity of available mineral nitrogen in grassland soils is dependant on the rate of mineralization of soil organic nitrogen (Coleman et al. 1983). The mineralization rate is determined by the rhizosphere microorganism biomass, and the microorganism biomass is limited by access to simple carbohydrate energy (Curl and Truelove 1986).

The available energy from soil organic matter is inadequate to increase soil microorganism biomass substantially. The small amount of readily accessible energy available to soil microorganisms in fresh organic material comes from short chain carbohydrates of sugars and starches composing only 1% to 5% and from water soluble proteins composing very low percentage (Brady 1974).

Grassland plants naturally leak small quantities of exudate substances that include sugars, amino acids, proteins, and numerous carbon compounds (Coyne et al. 1995). The quantity of root exudate leakage from ungrazed grassland plants is low and cannot support anything but a small microorganism biomass capable of performing biogeochemical processes only at low activity rates (Manske 2012c).

Partial defoliation that removes 25% to 33% of grass tillers biomass at vegetative phenological growth stages between the three and a half new leaf stage and the flower stage by large grazing graminivores causes great quantities of exudates containing simple carbohydrate energy to be released from the grass tillers through roots into the rhizosphere (Hamilton and Frank 2001, Manske 2011b). This increase in availability of energy from carbon compounds in the rhizosphere, increases the biomass and activity of the microorganisms (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). Increasing the rhizosphere organism biomass and activity results in greater rates of mineralization of soil organic nitrogen into mineral nitrogen available for plant use (Coleman et al. 1983, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005).

Differences in rhizosphere microorganism biomass and activity are directly related to the differences in the quantities of soil organic nitrogen mineralized into mineral nitrogen. The quantities of available mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), can be measured from soil samples.

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

When the quantity of available mineral nitrogen is between 100 lbs/ac and 165 lbs/ac (112 kg/ha-185 kg/ha) during periods of active plant growth, rangeland ecosystems can sustain herbage production at biological potential levels (Wight and Black 1972). Rangeland ecosystems that have soil mineral nitrogen available at quantities less than 100 lbs/ac (112 kg/ha) have a soil mineral nitrogen deficiency and are functioning below biological potential production capacity.

Procedure

Soil mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), was determined for the first time on the 1983-2018 Study grazing management practices in 1989 (during year 7) from silty ecological sites managed by four treatments: a) long-term nongrazed, b) seasonlong grazed 6.0 months, c) traditional seasonlong grazed 4.5 months, and d) twice-over rotation grazing strategy. During 1989, a mid June sample was collected using the standard technique for mixed soils of cropland sites with a bucket auger 2 inches (5.08 cm) in diameter and 6 inches (15.24 cm) long. Each treatment field sample included five soil cores to 12 inches (30.48 cm) in depth, located in a large circle, placed into a gallon bucket, and thoroughly mixed. Two replicate samples were selected from the bucket each consisting of about twenty percent of the collected soil material, placed on ice and frozen. 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 using wet chemistry methods.

Soil mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), was determined for replicated soil core samples collected in 2013, 2014, 2016, 2017, and 2018 from silty ecological sites managed by three treatments: a) long-term nongrazed, b) traditional seasonlong grazed 4.5 months, and c) twice-over rotation grazing strategy with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches. During 2013 and 2014, 6 monthly periods from May to October were collected and air dried. During 2016, 6 monthly periods from May to October were collected and frozen. During 2017, 2 monthly periods from June and August were collected and frozen. During 2018, 3 monthly periods from May, June, and July were collected and frozen. 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 using wet chemistry methods.

Results

The 6-year period (1987-1992) was a long period with near drought conditions receiving average perennial plant growing season (April to October) precipitation of 9.97 inches (68.90% of LTM). Drought conditions did occur during the growing season of 1988 receiving only 5.30 inches (36.65% of LTM) from April to October. During 1989, June received only 1.63 inches (51.10% of LTM) and during the 6 month growing season received 10.60

inches (73.30% of LTM) with water deficiency conditions occurring during July, August, and September.

During the seventh growing season, 1989, the rhizosphere microorganism biomass on the twice-over rotation treatment had increased sufficiently to mineralize greater than 100 lbs/ac of mineral nitrogen on all three pastures (table 31). The amount of available mineral nitrogen on the two seasonlong treatments was less than the threshold quantity of 100 lbs/ac (table 31). The amount of mineral nitrogen available on the long-term nongrazed treatment was slightly more than the threshold quantity (table 31).

The 2013-2014 soil samples for available mineral nitrogen were air dried awaiting analysis. The quantities of available ammonium on all sample dates on all three management treatments were unusually low, with a loss of about 60% of the ammonium, resulting in greatly reduced total available mineral nitrogen on all three management treatments (appendix tables 1, 2, and 3). The low quantity of remaining available ammonium was still 30% greater on the twice-over strategy than that on the nongrazed and was 15% greater than that on the seasonlong strategy. Available ammonium was 13% greater on the seasonlong strategy than that on the nongrazed grassland.

The 2016, 2017, and 2018 available mineral nitrogen data for the long-term nongrazed strategy are in appendix tables 4, 5, and 6, for the traditional seasonlong strategy are in appendix tables 7, 8, and 9, and for the twice-over rotation strategy are in appendix tables 10, 11, and 12.

The mean monthly precipitation of 2016 to 2018 had a total of 6 perennial plant growing season months (table 32). There were no months with water deficiency conditions. Low precipitation less than 75% of LTM occurred during May (16.7%). Normal precipitation greater than 75% and less than 125% of LTM occurred during June, July, and August (50.0%). High precipitation greater than 125% of LTM occurred during September and October (33.3%). Total 3 year mean growing season precipitation was normal at 13.77 inches (105.84% of LTM).

The 2016-2018 soil samples for available mineral nitrogen were frozen within a few hours of collection and presumably little of the available ammonium was lost. In rangeland soils most of the available mineral nitrogen is in the ammonium (NH_4) form with lower amounts in the nitrate (NO_3) form. From the 2016-2018 soil samples, mineral nitrogen was comprised of 90.6% NH_4 and 9.4% NO_3 on the nongrazed strategy, 89.9% NH_4 and 10.1% NO_3 on the seasonlong strategy, and 87.1% NH_4 and 12.9% NO_3 on the twice-over strategy.

The mean monthly total mineral nitrogen was 137.2 lbs/ac on the twice-over strategy (table 35) with 17.7 lbs/ac of nitrate and 119.5 lbs/ac of ammonium. Mean monthly total mineral nitrogen was 113.5 lbs/ac on the traditional seasonlong strategy (table 34) with 11.5 lbs/ac of nitrate and 102.0 lbs/ac of ammonium. Mean monthly total mineral nitrogen was 104.6 lbs/ac on the nongrazed strategy (table 33) with 9.8 lbs/ac of nitrate and 94.8 lbs/ac of ammonium. Total mineral nitrogen was 20.9% greater, ammonium was 17.1% greater, and nitrate was 55.0% greater on the twice-over strategy than that on the seasonlong strategy (tables 34 and 35). Total mineral nitrogen was 31.2% greater, ammonium was 26.1% greater, and nitrate was 80.6% greater on the twice-over strategy than that on the nongrazed strategy (tables 33 and 35). Total mineral nitrogen was 8.5% greater, ammonium was 7.7% greater, and nitrate was 16.5% greater on the seasonlong strategy than that on the nongrazed strategy (tables 33 and 34).

Available quantities of nitrate and ammonium for intact soils of rangeland sites fluctuate with changes in organic nitrogen mineralization by soil microbial activity and by immobilization of mineral nitrogen with changes in plant growth rate (Brady 1974, Goetz 1975, Legg 1975, Whitman 1975). The rates of the mineralization and immobilization processes are additionally affected by the quantity of soil water, and the biologically effectiveness of the grazing management strategy.

The quantity of available mineral nitrogen occurs in a dynamic cycle during each growing season that generally follows a typical pattern with some variations occurring on different ecological sites and at different soil depths (Goetz 1975). The variance in amplitude of the quantity of mineral nitrogen available between the peaks and low periods in the cycle oscillations usually is around 25% to 50%.

Mineralization and nitrification processes of soil microbe activity start slowly in early spring when soil temperature permits formation of liquid water around 30° F. Quantity of available mineral nitrogen increases with rising soil temperature and microorganism biomass reaching the first peak in mineral nitrogen around mid May, which is usually the greatest peak. Soon afterward, plant growth rates rapidly increase with plant growth activity greater than soil microbe activity resulting in the first low period during June and the first two weeks of July when the rapid growth of reproductive lead tillers slows. The second peak in mineral nitrogen is reached during late July to mid August as reproductive lead tiller growth moves into senescents and the slow growth rate of vegetative tillers start to increase. A second low period in mineral nitrogen occurs from mid August to late September as grass plants store carbohydrates during the winter hardening process and as fall tillers of cool season grasses and fall buds of warm season grasses develop, later to become vegetative tillers during the subsequent growing season. The third peak in mineral nitrogen occurs around mid October if some soil water is present and as perennial plant growth slows with decreasing air temperatures. Available mineral nitrogen declines during the third low period as soil temperatures decrease at the end of the growing season and winter freeze up approaches (Goetz 1975, Whitman 1975).

This typical dynamic cycle of available mineral nitrogen was followed on the silty ecological sites of the long-term nongrazed strategy (table 33) and the twice-over rotation strategy (table 35). The available mineral nitrogen on the traditional seasonlong strategy (table 34) followed the typical dynamic cycle during the first peak and low period and into the second peak, however, the second low period usually occurring from mid August to late September during the winter hardening and fall tiller and fall bud development processes appears to have been delayed until near the end of the growing season during October which would greatly reduce the winter survival chances for a high proportion of the carry over tillers resulting in lower grass density and decreased herbage biomass during the next growing season.

The four major internal grass plant growth mechanisms of precipitation (water) use efficiency, compensatory physiological processes, vegetative reproduction by tillering, and resource uptake competitiveness all require a threshold quantity of 100 lbs/ac (112 kg/ha) mineral nitrogen to be available before they can be fully activated. Traditional management practices that focus only on the aboveground ecosystem components rarely mineralize 100 lbs/ac of mineral nitrogen. Manske (2012b) documented quantities of available mineral nitrogen (table 36) on five long-term traditional management treatments with operational histories of 20 to 75 years that ranged from a low 31.2 lbs/ac on deferred grazing, to 39.5 lbs/ac on long-term nongrazing, to 42.4 lbs/ac and 61.6 lbs/ac on long duration seasonlong grazing, and to a high 76.7 lbs/ac on recommended duration (4.5 month) seasonlong grazing treatments. These low quantities of available mineral nitrogen that are well below the threshold level of 100 lbs/ac indicate that traditional grazing management and nongrazing practices are the direct cause of inhibitory mineral nitrogen deficiencies in rangeland ecosystems. The limiting factor on traditional practices is a low soil microbe biomass which are achlorophyllous and cannot fix carbon energy and must depend on the carbon energy fixed by grass plants during photosynthesis. However, releasing (exudation) of surplus grass plant carbon energy through the roots into the rhizosphere requires partial defoliation by large grazing graminivores when grass lead tillers are at vegetative phenological growth stages between the three and a half new leaf stage and the flower stage that occurs from early June to mid July. As a result of the increased carbon energy, the rhizosphere microbes can increase in biomass to a level that can mineralize 100 lbs/ac of nitrogen.

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 causing adequate quantities of fixed carbon energy to be exudated through the roots into the rhizosphere permitting an increase of the microorganism biomass to levels that are capable of mineralizing available mineral nitrogen at rates of 100 lbs/ac or greater that maintains full activation of the four major internal grass plant growth mechanisms.

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 increase the quantity of available fixed carbon, 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 increase herbage biomass production and improves herbage nutritional quality.

Full activation of the nutrient resource uptake processes increases root absorption of soil water and the major and minor essential elements, improves the robustness of grass growth and development, increases competitiveness of healthy grasses, and increases suppression of undesirable grass, weedy forb, and shrub seedlings or rhizomes from encroachment and establishment within grassland communities.

Full activation of the precipitation (water) use efficiency processes increases herbage biomass production 50.4% per inch of rainfall received, and reduces the detrimental effects during water deficiency periods and from drought conditions.

Discussion

The soil microorganism biomass and biological activity on the grazingland ecosystems managed with the twice-over rotation strategy were great enough to mineralize nitrogen at 112 lbs/ac to 157 lbs/ac during the grazing period of June to October. The soil microorganisms that occupy intact soil mostly inhibit that narrow zone around active perennial grass roots; the rhizosphere. Rhizosphere microorganisms are limited in production by access to energy from simple carbon chains. Grass plants fix large quantities of surplus carbon through photosynthesis during vegetative growth stages. The grazing periods on the twice-over rotation strategy are coordinated with grass tiller phenological growth and development. Partial defoliation by grazing graminivores that removes 25% to 33% of the aboveground leaf weight on about 60% to 80% of the lead grass tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage intentionally causes large quantities of grass leaf surplus simple carbohydrates to be exudated through the roots into the rhizosphere. The large increase in available simple carbon energy increases the microorganism biomass and elevates microbe activity increasing the quantity of mineralized nitrogen and other biogeochemical processes permitting the grassland ecosystem managed with the twice-over rotation strategy to function at the good - as - new biological potential production capacity.

The soil microorganism biomass and biological activity on the grazingland ecosystems managed with the traditional seasonlong strategy mineralized nitrogen at 97 lbs/ac to 122 lbs/ac during the June to October grazing period in a three year period that received normal growing season precipitation at 106% of LTM. Traditional seasonlong practices rarely mineralized nitrogen at rates greater than 100 lbs/ac. Seasonlong treatments are managed by long time traditional concepts that consider the things that can be seen aboveground i.e. the plants and the livestock. Unfortunately, the importance of the microorganisms belowground is not even acknowledged. The grazing periods on seasonlong strategies are not coordinated with grass tiller phenological growth stages; with grazing often starting before the three and a half new leaf stage and continuing past mid October. Some partial defoliation by grazing graminivores does cause exudation of quantities of carbohydrates at rates greater than typical leakage, however, multiple defoliation events and removal of greater than 50% leaf weight does not permit large quantities of simple carbon energy to be consistently released into the rhizosphere. Any enhancement of biological activity of microbes below that soil surface is purely unintentional. Usually the traditional management concepts and the characteristic seasonlong stocking rates cause quantities greater than 50% of the leaf weight to be removed from grass tillers. The remaining leaf area is insufficient to photosynthesize adequate quantities of carbohydrates to meet the demand for average growth. Without consistent large quantities of exudated simple carbon energy, the rhizosphere microorganism biomass on seasonlong managed ecosystems usually remain at mediocre levels and sometimes increase to higher quantities during good precipitation growing seasons.

The soil microorganism biomass and biological activity on grazingland ecosystem managed with a long-term nongrazed strategy mineralized nitrogen at 93 lbs/ac to 112 lbs/ac during the June to October grazing period in a three year period that received normal growing season precipitation at 106% of LTM on plant communities with greatly increased abundance of introduced replacement Canada bluegrass plants that have labile root material which provides a new source of carbon energy for soil microbes that native grass root material does not provide. On the nongrazed strategy, native grasses provide simple carbohydrate energy to soil microbes only at the typical low leakage rate. The lack of partial defoliation by grazing graminivores prevent large quantities of simple carbon energy from being exudated from grass roots into the rhizosphere, resulting in a small biomass of microorganisms and low quantities of available mineral nitrogen. The traditional purposes of the nongrazed treatment removes grazing defoliation by graminivores with the intention of resting the grazingland ecosystem as a restoration management practice developed from long-time concepts that do not go deeper than the soil surface. This misguided practice was based on a naive assumption that the observed vigor depletion of grassland communities was caused by livestock grazing, rather than being caused by poor management of livestock grazing, and that the lost vigor of the grass plants could be restored by resting. Ironically, removal of livestock grazing does not rest an ecosystem, the grass plants are not invigorated, and the soil microorganisms are not enhanced. The biomass of soil microorganisms on a nongrazed ecosystem can fluctuate with the soil moisture levels but cannot increase above the biomass that can be supported by the small quantities of carbon energy provided at the normal low leakage rate plus a small amount of carbon energy and water soluble crude protein remaining within recently dead plant residue. As a result, the microorganism biomass on nongrazed ecosystems remains small and the quantity of mineralized nitrogen remains low.

Rangelands of the Northern Plains are not inherently low producing ecosystems. The typical low grass herbage biomass and low calf weight gains on rangeland pastures managed with traditional grazing management practices result from deficient quantities of available soil mineral nitrogen below 100 lbs/ac. Rangelands with intact soils are not deficient in nitrogen. The biomass of rhizosphere microorganisms is too low to mineralize adequate quantities of organic nitrogen into the threshold quantity of 100 lbs/ac of mineral nitrogen required by grass plants to fully activate the four major internal growth mechanisms. The biomass of the rhizosphere microorganisms can be increased by implementation of the twice-over rotation strategy that consistently provide large quantities of surplus carbon energy from partially defoliated lead tillers to the microorganisms in the rhizosphere that in turn mineralize adequate quantities of mineral nitrogen for the plants that can then provide forage with adequate quantities of crude protein through the entire grazing season so cow and calf pairs can produce at their genetic potentials.

Table 31. Total mineral nitrogen (NO_3-N plus NH_4-N) in lbs/acre-foot collected in mid June from silty ecological sites managed by four treatments at DREC ranch, ND, 1989.

Management Treatment	Soil Depth (inches)	mid June
Long-term Nongrazed	0-12	106.05
Seasonlong grazed 6.0 m	0-12	61.61
Traditional seasonlong	0-12	76.70
Twice-over rotation	0-12	177.84
1st Pasture	0-12	199.05
2nd Pasture	0-12	163.97
3rd Pasture	0-12	170.50

Table 32. Precipitation in inches during perennial plant growing season months with mineral nitrogen soil samples collected, 2016-2018.

	May	Jun	Jul	Aug	Sep	Oct	Growing Season
Long-term Mean	2.65	3.19	2.36	1.96	1.50	1.35	13.01
2016-2018	1.74	2.49	2.81	2.27	2.66	1.80	13.77
% of LTM	65.66	78.06	119.07	115.82	177.33	133.33	105.84

Table 33. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac in incremental depths to 24 inches during growing season months on silty ecological sites of the long-term nongrazed, 2016-2018.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6	3.88	4.25	3.75	3.75	3.00	5.00
6-12	3.00	2.92	1.75	3.00	2.00	1.00
12-24	3.50	4.67	2.00	4.50	4.00	3.00
0-24	10.38	11.83	7.50	11.25	9.00	9.00
NH_4 ammonium						
0-6	39.73	32.50	38.10	40.63	30.67	44.70
6-12	31.21	31.22	28.15	31.25	28.88	31.98
12-24	27.13	27.03	26.03	28.31	24.80	26.27
0-24	98.06	90.75	92.27	100.18	84.35	102.95
$NO_3 + NH_4$						
0-6	43.61	36.75	41.85	44.38	33.67	49.70
6-12	34.21	34.14	29.90	34.25	30.88	32.98
12-24	30.63	31.70	28.03	32.81	28.80	29.27
0-24	108.44	102.58	99.77	111.43	93.35	111.95

Table 34. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac in incremental depths to 24 inches during growing season months on silty ecological sites of the traditional seasonlong, 2016-2018.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6	5.59	4.61	6.34	6.17	5.67	4.00
6-12	3.67	2.45	2.59	2.34	2.67	2.00
12-24	3.84	3.11	2.67	4.34	4.00	2.67
0-24	13.09	10.17	11.59	12.84	12.34	8.67
NH_4 ammonium						
0-6	47.18	40.61	40.60	45.88	48.40	37.09
6-12	36.25	31.02	28.37	28.69	34.59	27.19
12-24	31.90	31.43	25.21	26.98	26.32	24.36
0-24	115.33	103.06	94.17	101.54	109.31	88.64
$NO_3 + NH_4$						
0-6	52.77	45.22	46.93	52.04	54.07	41.09
6-12	39.92	33.46	30.95	31.02	37.26	29.19
12-24	35.74	34.55	27.87	31.31	30.32	27.03
0-24	128.42	113.23	105.75	114.39	121.65	97.31

Table 35. Mean mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), in lbs/ac in incremental depths to 24 inches during growing season months on silty ecological sites of the twice-over rotation system, 2016-2018.

Soil Depth (inches)	May	Jun	Jul	Aug	Sep	Oct
NO_3 nitrate						
0-6	8.67	7.11	6.59	8.25	5.00	6.67
6-12	7.17	4.17	3.00	4.67	2.00	6.67
12-24	6.84	6.00	2.34	5.34	6.67	9.33
0-24	22.68	17.28	11.92	18.25	13.67	22.67
NH_4 ammonium						
0-6	58.06	46.25	38.10	52.62	40.57	50.03
6-12	43.40	42.06	37.42	39.81	31.65	36.33
12-24	33.31	35.37	29.37	45.93	25.89	30.67
0-24	134.77	123.68	104.89	138.36	98.11	117.03
NO_3 + NH_4						
0-6	66.73	53.36	44.69	60.87	45.57	56.70
6-12	50.57	46.23	40.42	44.48	33.65	43.00
12-24	40.15	41.37	31.70	51.26	32.56	40.00
0-24	157.44	140.96	116.81	156.61	111.78	139.70

Table 36. Mineral nitrogen (lbs/ac) available on mixed grass prairie ecosystems effected by traditional management treatments.

Traditional Management Treatment	Operational Duration Years	Available Mineral Nitrogen lbs/ac
4.5 m Seasonlong	20 yr	76.7
6.0 m Seasonlong	20 yr	61.6
7.0 m Seasonlong	75 yr	42.4
Nongrazed	75 yr	39.5
Deferred Grazing	50 yr	31.2

Data from Manske 2012b.

D5. 2013-2018 Study, Soil Organic Matter (SOM) Affects Soil Quality

The quantity of soil organic matter (SOM) is a direct indication of soil primary productivity and is a sensitive measure of changes in soil quality and ecosystem functionality (Burke et al. 1989, Gregorich et al. 1994).

Increased quantities of microbe, plant, and animal biomass results in greater amounts of residue added annually to the soil organic matter. The quantity of organic matter in a soil can increase at annual increments until the steady state is reached where the inputs and the outputs are at equilibrium levels. The equilibrium level of soil organic matter is variable and affected by difference in soil texture, mean temperature, growing season precipitation, and type of management practice. Soil organic matter equilibrium level increases with reduction in the texture of the soils. Lower quantities of soil organic matter occur with coarse textured sandy soils and greater quantities occur in finer textured silty and clayey soils. The quantity of soil organic matter increases as mean temperatures cool and as growing season precipitation increases (Weaver et al. 1935, Brady 1974, Parton et al. 1987). The equilibrium level of soil organic matter for any specific soil type in a region can be decreased or increased depending on whether the effects from the type of management practice implemented causes a decrease or an increase in the soil microorganism biomass (Dormaar et al. 1977, Campbell and Sonster 1982, Naeth et al. 1991, McLaunchlan et al. 2006).

Soil organic matter is the primary nutrient reservoir of grassland ecosystems and contains the organic forms of the essential elements, carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S); the ionic forms of the macronutrients, calcium (Ca), magnesium (Mg), and potassium (K); and the ionic forms of the micronutrients, boron (B), copper (Cu), molybdenum (Mo), and zinc (Zn) (Brady 1974, Van Veen and Paul 1981, Burke et al. 1989). The other nine minor essential elements are present in grassland ecosystem soils in the mineral form at the same level as each element was present in the parent material.

Essential elements stored in the soil organic matter as unavailable organic forms or as ions adsorbed by colloidal complexes are biologically and chemically immobilized, respectively, and these stable forms are not subjected to potential losses through volatilization or leaching movement (Legg 1975, Gibson 2009). Availability of the immobilized essential elements is conducted through the ecosystem biogeochemical cycles performed by soil microorganisms (McGill and Cole 1981, Cheng and Johnson 1998, Manske 2012b, 2014c).

The quantity of available essential elements is determined by the rates of soil organic matter decomposition and mineralization that are directly regulated by the biomass of active soil microorganisms and are not affected by the quantity or rate of residue accession (Van Veen and Paul 1981). Increases in the organic matter content of a soil improves the stability of soil aggregates, improves the physical and chemical properties, improves air and water infiltration and water holding capacity, improves soil fertility, and increases cation exchange capacity (Schimel, Coleman, and Horton 1985, Six et al. 1998, 2004).

Procedure

The percent soil organic matter (SOM) was determined by the loss on ignition (% LOI) analysis conducted by the NDSU Soil Testing Laboratory from replicated soil core samples collected during June of 2013, 2014, 2016, 2017, and 2018 at silty ecological sites with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches on three management treatments a) long-term nongrazed, b) traditional seasonlong, and c) twice-over rotation strategy. During 2013 and 2014 the soil samples were air dried. During 2016 to 2018 the soil samples were frozen. The quantity of organic carbon and nitrogen in soil was determined from the weight of soil and the percent soil organic matter. The 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, and 12-24 inches (table 37). Weight of soil organic carbon (SOC) was determined from the weight of silty soil and percent of 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. Weight of soil organic nitrogen (SON) was determined from the 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 (table 35).

Table 37. Generalized soil bulk density and soil weight at incremental depths on silty ecological sites of rangeland in southwestern North Dakota.

Soil Depth (inches)	Soil Bulk Density (g/cm^3)	Soil Weight (lbs/ac)	 (tons/ac)
0-6	1.15	1,563,667.08	781.83
6-12	1.30	1,767,623.65	883.81
12-24	1.30	3,535,247.31	1,767.62
0-24		6,866,538.04	3,433.27

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

Table 38. Weight of soil, soil organic matter (SOM), soil organic carbon (SOC), and soil organic nitrogen (SON) in pounds per acre per incremental depth.

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

Results

The percent soil organic matter (SOM) on the long-term nongrazed strategy was 3.58% (0-6), 2.55% (6-12), and 2.43% (12-24). The percent soil organic matter (SOM) on the traditional seasonlong strategy was 6.30% (0-6), 3.20% (6-12), and 2.40% (12-24). The percent soil organic matter (SOM) on the twice-over rotation strategy was 7.15% (0-6), 4.50% (6-12), and 3.15% (12-24) during 2016-2018 (Figure 4). The percent SOM at 0-6 inch depth on the twice-over strategy was 13.5% greater than that on the seasonlong strategy and was 99.7% greater than that on the nongrazed strategy, and percent SOM on the seasonlong strategy was 76.0% greater than that on the nongrazed strategy. The percent SOM at 6-12 inch depth on the twice-over strategy was 40.6% greater than that on the seasonlong strategy and was 76.5% greater than that on the nongrazed strategy, and percent SOM on the seasonlong strategy was 25.5% greater than that on the nongrazed strategy. The percent SOM at 12-24 inch depth on the twice-over strategy was 31.3% greater than that on the seasonlong strategy and was 29.6% greater than that on the nongrazed strategy, and percent SOM on the seasonlong strategy was 1.2% lower than that on the nongrazed strategy (Figure 4).

The quantity of soil organic matter (SOM) on the silty ecological sites to the 24 inch soil depth on the long-term nongrazed strategy was 66.3 tons/ac during 2013-2014 and was 93.5 tons/ac during 2016-2018 with an increase of 40.9% (tables 39 and 40). One of the replicate nongrazed exclosures was lost to oil exploration during this study. The elimination of data from this lost site caused most of the change in the mean quantity of soil organic matter, organic carbon, and organic nitrogen. The quantity of soil organic matter (SOM) to the 24 inch soil depth on the traditional seasonlong strategy was 122.3 tons/ac during 2013-2014 and was 120.0 tons/ac during 2016-2018 with a decrease of 1.9% (tables 41 and 42). The quantity of soil organic matter (SOM) to the 24 inch soil depth on the twice-over rotation strategy was 143.4 tons/ac during 2013-2014 and was 151.4 tons/ac during 2016-2018 with a increase of 5.6% (tables 43 and 44). During 2013-2014, the quantity of SOM on the seasonlong strategy was 84.3% greater than that on the nongrazed strategy (tables 39 and 41). The quantity of SOM on the twice-over strategy was 116.2% greater than that on the nongrazed (tables 39 and 43) and was 17.3% greater than that on the seasonlong strategy (tables 41 and 43). During 2016-2018, the quantity of SOM on the seasonlong strategy was 28.3% greater than that on the nongrazed strategy (tables 40 and 42). The quantity of SOM on the twice-over strategy was 61.9% greater than that on the nongrazed (tables 40 and 44) and was 26.2% greater than that on the seasonlong strategy (tables 42 and 44).

Soil organic matter (SOM) has been accumulating in the top 24 inches of soil at mean rates of 5193 lbs/ac/yr, 6664 lbs/ac/yr, and 8408 lbs/ac/yr on the nongrazed, seasonlong, and twice-over strategies, respectively, with rates of 2807 lbs/ac/yr, 4307 lbs/ac/yr, and 5315 lbs/ac/yr in the top 12 inches of soil and at rates of 2386 lbs/ac/yr, 2357 lbs/ac/yr, and 3093 lbs/ac/yr in the second 12 inches of soil, respectively. The rate of soil organic matter (SOM) accumulation on the seasonlong strategy was 28.6% greater than that on the nongrazed strategy. The rate of soil organic matter (SOM) accumulation on the twice-over strategy was 62.2% greater than that on the nongrazed and was 26.1% greater than that on the seasonlong strategy.

The quantity of soil organic carbon (SOC) on the silty ecological sites to the 24 inch soil depth on the long-term nongrazed strategy was 38.5 tons/ac during 2013-2014 and was 54.2 tons/ac during 2016-2018 with an increase of 40.7% (tables 39 and 40). The quantity of soil organic carbon (SOC) to the 24 inch soil depth on the traditional seasonlong strategy was 70.9 tons/ac during 2013-2014 and was 69.8 tons/ac during 2016-2018 with a decrease of 1.6% (tables 41 and 42). The quantity of soil organic carbon (SOC) to the 24 inch soil depth on the twice-over rotation strategy was 83.2 tons/ac during 2013-2014 and was 87.9 tons/ac during 2016-2018 with a increase of 5.7% (tables 43 and 44). During 2013-2014, the quantity of SOC on the seasonlong strategy was 84.4% greater than that on the nongrazed strategy (tables 39 and 41). The quantity of SOC on the twice-over strategy was 116.0% greater than that on the nongrazed (tables 39 and 43) and was 17.3% greater than that on the seasonlong strategy (tables 41 and 43). During 2016-2018, the quantity of SOC on the seasonlong strategy was 28.8% greater than that on the nongrazed strategy (tables 40 and 42). The quantity of SOC on the twice-over strategy was 62.2% greater than that on the nongrazed (tables 40 and 44) and was 25.9% greater than that on the seasonlong strategy (tables 42 and 44).

Soil organic carbon (SOC) has been accumulating in the top 24 inches of soil at mean rates of 3010 lbs/ac/yr, 3878 lbs/ac/yr, and 4881 lbs/ac/yr on the nongrazed, seasonlong, and twice-over strategies, respectively. The rate of soil organic carbon (SOC) accumulation on the seasonlong strategy was 27.8% greater than that on the nongrazed strategy. The rate of soil organic carbon (SOC) accumulation on the twice-over strategy was 61.6% greater than that on the nongrazed and was 26.4% greater than that on the seasonlong strategy.

The quantity of soil organic nitrogen (SON) on the silty ecological sites to the 24 inch soil depth on the long-term nongrazed strategy was 3.9 tons/ac during 2013-2014 and was 5.4 tons/ac during 2016-2018 with an increase of 41.3% (tables 39 and 40). The quantity of soil organic nitrogen (SON) to the 24 inch soil depth on the traditional seasonlong strategy was 7.1 tons/ac during 2013-2014 and was 7.1 tons/ac during 2016-2018 with a decrease of 0.6% (tables 41 and 42). The quantity of soil organic nitrogen (SON) to the 24 inch soil depth on the twice-over rotation strategy was 8.3 tons/ac during 2013-2014 and was 9.0 tons/ac during 2016-2018 with a increase of 8.5% (tables 43 and 44). During 2013-2014, the quantity of SON on the seasonlong strategy was 84.2% greater than that on the nongrazed strategy (tables 39 and 41). The quantity of SON on the twice-over strategy was 116.1% greater than that on the nongrazed (tables 39 and 43) and was 17.4% greater than that on the seasonlong strategy (tables 41 and 43). During 2016-2018, the quantity of SON on the seasonlong strategy was 29.6% greater than that on the nongrazed strategy (tables 40 and 42). The quantity of SON on the twice-over strategy was 66.0% greater than that on the nongrazed (tables 40 and 44) and was 28.1% greater than that on the seasonlong strategy (tables 42 and 44).

Soil organic nitrogen (SON) has been accumulating in the top 24 inches of soil at mean rates of 304.9 lbs/ac/yr, 381.1 lbs/ac/yr, and 495.5 lbs/ac/yr on the nongrazed, seasonlong, and twice-over strategies, respectively. The rate of soil organic nitrogen (SON) accumulation on the seasonlong strategy was 25.0% greater than that on the nongrazed strategy. The rate of soil organic nitrogen (SON) accumulation on the twice-over strategy was 62.5% greater than that on the nongrazed and was 30.0% greater than that on the seasonlong strategy.

Discussion

The major essential elements of carbon, hydrogen, nitrogen, and oxygen have separate but closely linked biogeochemical cycles that transform the elements between organic forms and inorganic forms. Large quantities of the major essential elements are retained in the soil organic matter of grassland ecosystems as immobilized organic compounds. Soil microorganisms cycle a portion of the major essential elements from organic detritus into inorganic forms each growing season. The quantity of essential elements mineralized by soil microorganisms is a major factor that determines the quantity of annual biomass production.

Soil organisms and grassland plants use the essential elements in the inorganic form to synthesize vital organic compounds of carbohydrates, proteins, and nucleic acids. Grass plants produce double the quantity of leaf biomass than needed for normal plant growth (Crider 1955, Coyne et al. 1995). All of the aboveground herbage biomass produced by perennial grasses in a growing season represents about 33% of the total biomass production. About 67% of the annual perennial grass biomass is produced belowground. About 50% of the aboveground biomass is expendable by the plant. About half of the expendable leaf material is removed as senescent leaves that are broken from the plant and fall to the ground, or as leaf material consumed by insects and wildlife. About half of the expendable leaf material, or 25% of the aboveground biomass can be consumed by grazing livestock.

Perennial grass leaf material consists of digestible nutrients and nondigestible structural components. About 15% of the nutrients contained in the consumed leaf material is extracted by stocker heifers and steers and retained for growth. About 30% of the nutrients contained in the consumed leaf material is extracted by lactating cows, with a portion retained by the cow for production, and the remainder of the extracted nutrients passed on to her calf for growth (Russelle 1992, Gibson 2009).

All of the nondigestible dry matter and most of the nutrients consumed by grazing livestock are deposited on the ground as manure in a couple of days. Most of the nutrients consumed and used by livestock for maintenance are returned to the ecosystem in the feces and urine. None of the herbage biomass dry matter produced during a growing season is removed by livestock from the grazingland ecosystem. All of the essential elements contained in the belowground biomass and those contained in the nonconsumed aboveground biomass stay in the ecosystem. Nearly all of the essential elements use in the annual production of herbage biomass and soil organism biomass are retained and recycled in the ecosystem.

Some major essential elements are lost or removed from the ecosystem as output. The metabolic process of respiration in soil organisms, plants, and animals results in a loss of some essential elements as carbon dioxide, water vapor, and heat energy. Some essential elements are removed from the ecosystem as weight biomass produced by insects and wildlife. The essential elements transferred from grass plants to grazing animals and used for animal growth are removed from the ecosystem (Gibson 2009). If the grassland ecosystem is burned, almost all of the essential elements in the aboveground herbage are volatilized, and if the soil is dry, some of the belowground essential elements are also lost (Russelle 1992).

The small proportion of the ecosystem major essential elements that are lost or removed annually need to be replenished by capturing major essential elements as input through ecosystem processes. Atmosphere carbon dioxide is the ecosystem input for carbon. Precipitation of water is the ecosystem input for hydrogen. Wet deposition of nitrogen oxides following lightning discharges is the ecosystem input for nitrogen. Carbon dioxide, water, and nitrogen oxides are the ecosystem input for oxygen. Radiant light from the sun is the ecosystem input for energy. The input source of major essential elements are not part of the ecosystem resources until the ecosystem processes capture the input essential elements.

The grassland ecosystems managed with the twice-over strategy annually captured 1003 lbs/ac greater organic carbon than that captured on the ecosystems managed with the seasonlong strategy, and annually captured 1870 lbs/ac greater organic carbon that that captured on the ecosystems managed with the nongrazed strategy, and the annually captured organic carbon on the ecosystem managed with the seasonlong strategy were 867 lbs/ac greater than that captured on the ecosystems managed with the nongrazed strategy.

The grassland ecosystems managed with the twice-over strategy annually captured 114 lbs/ac greater organic nitrogen than that captured on the ecosystems managed with the seasonlong strategy and annually captured 191 lbs/ac greater organic nitrogen than that captured on the ecosystems managed with the nongrazed strategy, and the annually captured organic nitrogen on the ecosystems managed with the seasonlong strategy were 76 lbs/ac greater than that captured on the ecosystems managed with the nongrazed strategy.

The grassland ecosystems managed with the twice-over strategy annually captured 1744 lbs/ac greater organic matter than that captured on the ecosystems managed with the seasonlong strategy and annually captured 3215 lbs/ac greater organic matter than that captured on the ecosystems managed with the nongrazed strategy, and the annually captured organic matter on the ecosystems managed with the seasonlong strategy were 1471 lbs/ac greater than that captured on the ecosystems managed with the nongrazed strategy.

The quantities of annually captured major essential elements were greater on the ecosystems managed with the twice-over strategy, while the quantities of annually captured major essential elements were lowest on the ecosystems managed with the nongrazed strategy, and the quantities of annually captured major essential elements on the ecosystems managed with the seasonlong strategy were in between.

The twice-over rotation grazing system is the biologically effective management strategy that was intentionally designed to increase the soil rhizosphere microorganism biomass enough to mineralize between 100 lbs/ac and 165 lbs/ac of mineral nitrogen and inorder to fully activate the four major internal grass plant growth mechanisms and to perform the other ecosystem biogeochemical processes at biologically potential levels in order to capture great enough quantities of major essential elements to completely replace the quantities that are annually lost or removed from the ecosystem.

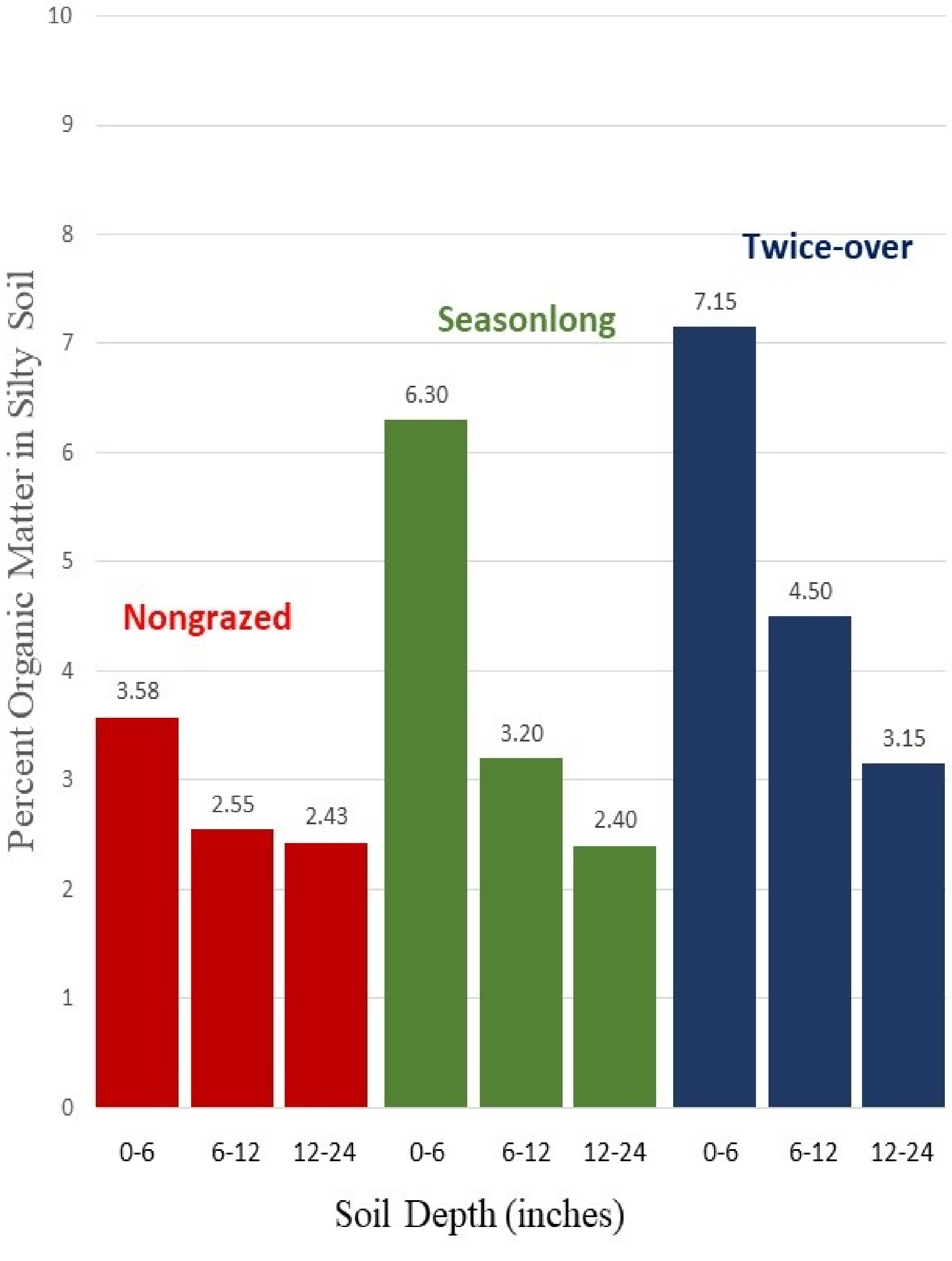

Figure 4. Distribution of organic matter (SOM) at incremental depths to 24 inches during June on silty ecological sites, 2016-2018

Table 39. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the long-term nongrazed, 2013-2014.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	3.08	1.89	1.45	1.93
lbs/ac	48,053.99	33,333.89	51,281.84	132,669.72
tons/ac	24.03	16.67	25.64	66.33
SOC				
%	1.79	1.10	0.84	1.12
lbs/ac	27,927.48	19,400.68	29,708.10	77,036.26
tons/ac	13.96	9.70	14.85	38.52
SON				
%	0.18	0.11	0.08	0.11
lbs/ac	2,792.74	1,940.07	2,970.81	7,703.62
tons/ac	1.40	0.97	1.49	3.85

Table 40. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the long-term nongrazed, 2016-2018.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	3.58	2.55	2.43	2.72
lbs/ac	55,979.28	45,074.40	85,906.51	186,960.19
tons/ac	27.99	22.54	42.95	93.48
SOC				
%	2.07	1.48	1.41	1.58
lbs/ac	32,367.91	26,160.83	49,846.99	108,375.75
tons/ac	16.18	13.08	24.92	54.18
SON				
%	0.21	0.15	0.14	0.16
lbs/ac	3,283.70	2,651.44	4,949.35	10,884.49
tons/ac	1.64	1.33	2.47	5.44

Table 41. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the traditional seasonlong, 2013-2014.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	6.07	3.38	2.55	3.56
lbs/ac	94,703.80	59,612.99	90,185.30	244,502.09
tons/ac	47.35	29.81	45.09	122.25
SOC				
%	3.52	1.96	1.48	2.07
lbs/ac	54,918.84	34,568.48	52,342.84	141,830.16
tons/ac	27.46	17.28	26.17	70.90
SON				
%	0.35	0.20	0.15	0.21
lbs/ac	5,491.88	3,456.85	5,234.28	14,183.01
tons/ac	2.75	1.73	2.62	7.09

Table 42. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the traditional seasonlong, 2016-2018.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	6.30	3.20	2.40	3.49
lbs/ac	98,511.03	56,563.96	84,845.94	239,920.93
tons/ac	49.26	28.28	42.42	119.96
SOC				
%	3.66	1.86	1.40	2.03
lbs/ac	57,230.22	32,877.80	49,493.46	139,601.48
tons/ac	28.12	16.44	24.75	69.80
SON				
%	0.37	0.19	0.14	0.21
lbs/ac	5,785.57	3,358.48	4,949.35	14,043.40
tons/ac	2.89	1.68	2.47	7.05

Table 43. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the twice-over rotation system, 2013-2014.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	5.98	4.19	3.38	4.18
lbs/ac	93,299.62	73,898.95	119,539.74	286,738.31
tons/ac	46.65	36.95	59.77	143.37
SOC				
%	3.47	2.43	1.96	2.42
lbs/ac	54,138.74	42,857.86	69,318.90	166,315.50
tons/ac	27.07	21.43	34.66	83.16
SON				
%	0.35	0.24	0.20	0.24
lbs/ac	5,413.87	4,285.79	6,931.89	16,631.55
tons/ac	2.71	2.14	3.47	8.32

Table 44. Soil organic components, soil organic matter (SOM), carbon (SOC), and nitrogen (SON), at incremental depths to 24 inches during June on the silty ecological sites of the twice-over rotation system, 2016-2018.

	Soil Depth (inches)			
Soil Organic Components	0-6	6-12	12-24	0-24
SOM				
%	7.15	4.50	3.15	4.41
lbs/ac	111,802.20	79,543.06	111,360.29	302,705.55
tons/ac	55.90	39.77	55.68	151.35
SOC				
%	4.15	2.61	1.83	2.56
lbs/ac	64,892.18	46,134.98	64,695.03	175,722.19
tons/ac	32.45	23.07	32.35	87.86
SON				
%	0.42	0.27	0.19	0.26
lbs/ac	6,567.40	4,772.58	6,716.97	18,056.95
tons/ac	3.28	2.39	3.36	9.03

D6. 2016-2018 Study, Evaluation of Soil Microbe Biomass and Activity

Soil functions are directly or indirectly related to the soil microorganisms. The soil biogeochemical processes are driven by the biomass and activity of soil microbes. Soil microorganisms recycle the essential elements required for life on earth. Measuring soil microbe biomass and activity is fundamental to understanding and managing the processes performed by these critical organisms. However, measuring the biomass and activity of soil microbes is a perplexing difficulty.

These critters are tiny, microzoan, less than 0.5 microns in diameter, with one thousand microns equal to one millimeter. Most of these soil organisms cannot be cultured on agar plates. Fortunately, microbial cell membranes contain phospholipid fatty acids (PLFA's). The PLFA's can be extracted from soil samples with the amount of total PLFA's indicating the viable microbial biomass and the various different lipid classes serving as unique signatures (biomarkers) for specific functional groups of microorganisms.

The microbes in cropland mixed soils in which annual plants grow are all free-living in the soil edaphosphere (earth sector or zone). Some of these microbes do not associate with plants. Two types of free-living microbes associate with plants, some of these microbes are plant-detrimental (pathogenic) and some are plant-beneficial. The free-living plant-beneficial microbes live in a zone of unaltered soil surrounding active annual roots. This volume of loose soil is called a rhizosphere which exists only as long as the annual root remains active.

The microbes in intact soils of grasslands in which perennial plants grow are symbiotic with the plants and inhabit a cylinder of soil particles bonded by fungal secreted adhesive polysaccharides that surrounds perennial roots are also called a rhizosphere (root sector or zone). The rhizosphere microorganisms perform grassland ecosystem biogeochemical processes that renew nutrient flow activities in the intact soil. Biogeochemical processes transform stored essential elements from organic forms into plant-usable inorganic forms. These biogeochemical processes also capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen, with assistance from active live plants, and transform them into storage as organic forms for later use. And they also decompose complex unusable organic material into compounds and then into reusable essential elements (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). The quantity of biogeochemical processes taking place in grassland ecosystems is dependent on the rhizosphere volume and microorganism biomass (Coleman et al. 1983). Both these factors are limited by access to simply carbohydrate energy (Curl and Truelove 1986). Healthy grass plants produce double the quantity of leaf biomass (Crider 1955; Coyne et al. 1995), capture and fix large amounts of carbon during photosynthesis, and produce carbohydrates in quantities greater than the amount required for normal growth and maintenance (Coyne et al. 1995). Partial defoliation of grass tillers at the vegetative phenological growth stages by large grazing graminivores cause significant quantities of exudates containing simple carbohydrates to be released from the grass tillers through the roots into the rhizosphere (Hamilton and Frank 2001). As a consequence, the biomass and activity of microorganisms also increase (Anderson et al. 1981; Curl and Truelove 1986; Whipps 1990), resulting in greater biogeochemical cycling of essential elements (Coleman et al. 1983; Biondini et al. 1988; Klein et al. 1988; Burrows and Pfeger 2002; Rillig et al. 2002; Bird et al. 2002; Driver et al. 2005).

The rhizosphere is comprised of bacteria, protozoa, nematodes, springtails, mites, endomycorrhizal fungi, and ectomycorrhizal fungi. Bacteria are microscopic single-celled saprophitic organisms that collectively consume large quantities of soil organic matter and are one of the primary producers of the rhizosphere. Protozoa are single-celled microorganisms that are mainly small amoeba and feed primarily on bacteria. Nematodes are a diverse group of small nonsegmented worms. Most nematodes feed on bacteria or fungi, some feed on protozoa, and some eat other nematodes. Springtails are the most abundant insect in grassland soils and they ingest considerable quantities of soil organic matter in order to eat fungi and bacteria. Mites are small eight-legged arachnids that feed on fungi, nematodes, small insects, and other mites. The nematodes, springtails, and mites travel among rhizosphere structures. Fungi are achlorophyllous saprophytes that live on dead organic matter. Endomycorrhizal fungi develop arbuscules, vesicles, and hyphae within root tissue of the host plant and secrete adhesive polysaccharides that bond soil particles around grass roots forming the structural environment for rhizosphere organisms. Ectomycorrhizal fungi develop a sheath around the root with hyphae and do not enter the tissue of the host plant (Harley and Smith 1983). The bacteria and fungi are the microflora saprotrophic organisms at the bottom of the food chain and makeup the greatest biomass of the rhizosphere.

Most European Union (EU) countries established programs to monitor soil quality and the state of biodiversity following the adoption of the Treaty on Biological Diversity of Rio de Janeiro in 1992. As a result, refined microbiological methods for assessing soil quality required development with contributions from many countries over a period from 1992 until 2006. This research activity in EU countries stimulated the development of specific methods for Soil Health Analysis for North American soils conducted over a period from 1996 to 2011. Development of these new sophisticated methods are important because soil quality and ecosystem biogeochemical processes depend on the biomass and activity levels of microorganisms which perform the key functions in decomposition and nutrient cycling.

Soil microbe biomass and activity in grassland ecosystems of the Northern Mixed Grass Prairie were evaluated using the recently developed methods for the Haney-Soil Health Analysis conducted at the Ward Laboratories, Kearney, NE.

Procedure

Biomass of functional groups of soil microbes, including Total Microbes, Total Bacteria, Total Fungi, Protozoa, and Unknown, were determined by phospholipid fatty acid (PLFA) analysis. Microbial activity in soil was measured with the Solvita 1-day CO_2-C procedure that determined soil biological CO_2 respiration from the quantity of CO_2-C in ppm released in 24 hr from soil microbes after the soil had been dried and rewetted. Percent organic matter (% LOI), soluble salts, and soil pH were determined by standard methods. Total organic carbon and total nitrogen were determined by the water extraction method. Inorganic nitrogen (both nitrate and ammonium), and total phosphorus (both organic and inorganic) were determined by the plant organic acids (H3A) extraction method. Plant essential elements of Potassium, Calcium, Magnesium, Sulfur, Iron, Manganese, Zinc, and Copper, plus Sodium, and Aluminum were analyzed by the plant organic acids (H3A) extraction method. These analysis were conducted by the Ward Laboratory in Kearney, NE, on replicated soil core samples collected with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches on silty ecological sites of three management strategies: a) long-term nongrazed, b) traditional seasonlong, and c) twice-over rotation system during June and July monthly periods 2016 and 2018 and during June 2017.

Results

During the 3 year period of 2016 to 2018, the mean June and July precipitation was normal at 4.60 inches (82.88% of LTM). During 2016, June and July received 5.57 inches (100.36% of LTM). During 2017, June and July received 1.99 inches (35.86% of LTM). And during 2018, June and July received 6.24 inches (112.43% of LTM).

During 2016 to 2018, relatively new soil biological methods were used to analyze soil microbe activity. Annual data analyzed by the Salvita CO_2 and PLFA (phospholipid fatty acid) analysis are in appendix tables 22 to 24. Annual data analyzed by standard methods and water extraction are in appendix tables 25 to 27. Annual data analyzed by H3A (plant organic acids) extraction are in appendix tables 28 to 35.

Aerobic respiration by soil microbes uses oxygen to metabolize carbohydrates in order to gain chemical energy; complete oxidation during this process releases carbon dioxide and water. The quantity of carbon dioxide (CO_2) released in 24 hours indicates the level of microorganism activity. The weight of microbial carbon dioxide released in 24 hours on the twice-over strategy was 1265.37 lbs/ac CO_2 with a microbe biomass of 8014.30 ng/g, on the seasonlong strategy microbial activity released 1091.20 lbs/ac CO_2 with a microbe biomass of 8882.92 ng/g, and on the nongrazed strategy microbial activity released 752.53 lbs/ac CO_2 with a microbe biomass of 7024.04 ng/g (table 45). The quantity of CO_2 released on the seasonlong was 45.0% greater with a 26.5% greater microbe biomass than that on the nongrazed strategy. The quantity of CO_2 released on the twice-over strategy was 68.2% greater with a 14.1% greater microbe biomass than that on the nongrazed strategy, and the quantity of CO_2 released was 16.0% greater with a 9.8% smaller microbe biomass than that on the seasonlong strategy.

The biomass of fungi was 814.69 ng/g (11.6%) on the nongrazed strategy, 1040.55 ng/g (11.7%) on the seasonlong strategy, and 1146.40 ng/g (14.3%) on the twice-over strategy (table 45). Fungi biomass on the twice-over strategy was 40.7% greater than that on the nongrazed strategy and was 10.2% greater than that on the seasonlong strategy. Fungi biomass on the seasonlong strategy was 27.7% greater than that on the nongrazed strategy.

The biomass of protozoa was 32.16 ng/g (0.5%) on the nongrazed strategy, 41.47 ng/g (0.5%) on the seasonlong strategy, and 42.07 ng/g (0.5%) on the twice-over strategy (table 45). Protozoa biomass on the twice-over strategy was 30.8% greater than that on the nongrazed strategy and was 1.5% greater than that on the seasonlong strategy. Protozoa biomass on the seasonlong strategy was 29.0% greater than that on the nongrazed strategy.

The biomass of bacteria was 3288.40 ng/g (46.8%) on the nongrazed strategy, 4206.22 ng/g (47.4%) on the seasonlong strategy, and 3794.91 ng/g (47.4%) on the twice-over strategy (table 45). Bacteria biomass on the seasonlong strategy was 27.9% greater than that on the nongrazed strategy, and was 10.8% greater than that on the twice-over strategy. Bacteria biomass on the twice-over strategy was 15.4% greater than that on the nongrazed strategy.

The biomass of unknown microbes was 2888.26 ng/g (41.1%) on the nongrazed strategy, 3607.42 ng/g (40.6%) on the seasonlong strategy, and 3032.37 ng/g (37.8%) on the twice-over strategy (table 45). Unknown microbe biomass on the seasonlong strategy was 24.9% greater than that on the nongrazed strategy, and was 19.0% greater than that on the twice-over strategy. Unknown microbe biomass on the twice-over strategy was 5.0% greater than that on the nongrazed strategy.

The quantity of unknown microbes was about 40% of the total microbe biomass which was a large portion, most likely related to being from grassland soils rather than from cropland soils. Only 0.5% of the microbe biomass was identified as protozoan which was extremely low and assumed that most grassland protozoa are unknown in cropland soils.

Soil pH is the relationship of the activity of the hydrogen ions related to the activity of the hydroxyl ions. When the quantity of hydrogen ions is increasingly greater than the quantity of hydroxyl ions, the soil acidity becomes greater. When the quantity of hydroxyl ions is increasingly greater than the quantity of hydrogen ions, the soil alkalinity becomes greater. When the quantity of hydrogen ions and the quantity of hydroxyl ions are balanced, the soil is neutral. The soil pH at incremental depths to 24 inches during June and July on the silty ecological sites of all management strategies at all soil depths were neutral, except the 12-24 inch soil depth on the twice-over strategy was moderately alkaline (table 46).

The quantity of soluble salts are measured by electrical conductivity (EC in mmhos/cm) to indicate relative degree of growth problems from salts for plants; at low concentrations of soluble salts, plant growth is unimpeded and at high concentrations of soluble salts, the salts become toxic and hinder plant growth. The quantity of soluble salts at incremental depths to 24 inches during June and July on the silty ecological sites of all management strategies at all soil depths were low causing no problems for plant growth (table 46).

Soil organic matter (SOM) is a portion of a soil comprised of organic plant and animal residue at various stages of decomposition and is the primary nutrient reservoir for essential elements. The quantity of soil organic matter (SOM) analyzed by the new methods were 22.8% lower on the nongrazed, 10.6% lower on the seasonlong, and 24.0% lower on the twice-over strategies than that analyzed by the traditional methods from replicate soil samples. The soil organic matter on the twice-over strategy was 59.5% greater than that on the nongrazed strategy, and was 7.4% greater than that on the seasonlong strategy. The soil organic matter on the seasonlong strategy was 48.6% greater than that on the nongrazed strategy (table 46).

Carbon and nitogen are extremely important major essential elements. The water extractable organic carbon (WEOC) is a very small portion of carbon energy from the soil organic matter (SOM) that is readily available to soil microbes. The WEOC was 1.6% of SOM on the nongrazed strategy, the WEOC was 1.2% of SOM on the seasonlong strategy, and the WEOC was 1.5% of SOM on the twice-over strategy (table 46). The WEOC on the nongrazed strategy was 61.7 times smaller than the SOM, on the seasonlong strategy the WEOC was 83.9 times smaller than the SOM, and on the twice-over strategy the WEOC was 66.6 times smaller than the SOM. The quantity of WEOC on the twice-over strategy was 35.0% greater than that on the seasonlong strategy and was 47.6% greater than that on the nongrazed strategy, and WEOC on the seasonlong strategy was 9.3% greater than that on the nongrazed strategy.

The water extractable organic nitrogen (WEON) is an extremely small portion of the total soil nitrogen from the soil organic matter (SOM) and is the minute quantity available to soil microbes that is easily broke down into inorganic nitrogen forms. The WEON on the nongrazed strategy was 0.11% of SOM, the WEON was 0.08% of SOM on the seasonlong strategy, and the WEON was 0.10% of SOM on the twice-over strategy (table 46). The quantity of WEON on the twice-over strategy was 28.2% greater than that on the seasonlong strategy and was 35.8% greater than that on the nongrazed strategy, and WEON on the seasonlong strategy was 6.0% greater than that on the nongrazed strategy.

H3A is a produced mixture of organic acids used in soil test laboratories as a soil extractant that mimics the plant roots' natural process for acquiring nutrients unassisted by symbiotic soil microbes. Inorganic nitrogen analyzed by H3A extraction had much lower results than traditional wet chemistry. Nitrate determined by H3A extraction was about 2.1% lower than nitrate determined by wet chemistry and ammonium determined by H3A extraction was about 68.6% lower than ammonium determined by wet chemistry. Mineral nitrogen analyzed by H3A plant organic acid extract was 59.08 lbs/ac with 14.73 lbs/ac of nitrate and 44.35 lbs/ac of ammonium of the twice-over strategy. Mineral nitrogen was 40.54 lbs/ac with 11.38 lbs/ac of nitrate and 29.16 lbs/ac of ammonium on the seasonlong strategy. Mineral nitrogen was 32.12 lbs/ac with 8.54 lbs/ac of nitrate and 23.58 lbs/ac of ammonium on the nongrazed strategy (table 47). Mineral nitrogen was 45.7% greater, ammonium was 52.1% greater, and nitrate was 29.4% greater on the twice-over strategy than that on the seasonlong strategy. Mineral nitrogen was 83.9% greater, ammonium was 88.1% greater, and nitrate was 72.5% greater on the twice-over strategy than that on the nongrazed strategy. Mineral nitrogen was 26.2% greater, ammonium was 23.7% greater, and nitrate was 33.3% greater on the seasonlong strategy than that on the nongrazed strategy (table 47).

Phosphorus, potassium, calcium, magnesium, and sulfur are macronutrients required by both plants and animals. Sodium is a macronutrient required by animals and used by warm season plants and cacti. Iron, manganese, zinc, and copper are micronutrients required by both plants and animals. Carbon, nitrogen, phosphorus, and sulfur have both organic and inorganic forms that require soil microbe activity for transformation to be plant available. Calcium, magnesium, potassium, zinc, and copper have ionic forms that are chemically immobilized as ionic-colloidal complexes that require soil microbe activity to be plant available. These macro- and micronutrients extracted from soil by H3A plant organic acids mimic the natural process used by plant roots unaided by soil microbes and are thus only a small portion of the macro- and micronutrients present in the soil, albeit, not as readily available as the portion extracted by H3A and require soil microbe action to be plant available.

Phosphorus analyzed by H3A plant organic acid extract was 91.85 lbs/ac with 38.50 lbs/ac organic and 53.35 lbs/ac inorganic on the twice-over strategy. Total phosphorus was 77.27 lbs/ac with 42.05 lbs/ac organic and 35.22 lbs/ac inorganic on the seasonlong strategy. Total phosphorus was 84.33 lbs/ac with 39.65 lbs/ac organic and 44.68 lbs/ac inorganic on the nongrazed strategy (table 47). Total phosphorus was 18.9% greater, organic was 8.4% lower, and inorganic was 51.5% greater on the twice-over strategy than that on the seasonlong strategy. Total phosphorus was 8.9% greater, organic was 2.9% lower, and inorganic was 19.4% greater on the twice-over strategy than that on the nongrazed strategy. Total phosphorus was 8.4% lower, organic was 6.1% greater, and inorganic was 21.2% lower on the seasonlong strategy than that on the nongrazed strategy (table 47).

The macronutrient potassium (K) analyzed by H3A plant organic acid extract was 1414.50 lbs/ac on the twice-over strategy, 1179.34 lbs/ac on the seasonlong strategy, and 1033.05 lbs/ac on the nongrazed strategy (table 48). Potassium on the twice-over strategy was 36.9% greater than that on the nongrazed strategy, and was 19.9% greater than that on the seasonlong strategy. Potassium on the seasonlong strategy was 14.2% greater than that on the nongrazed strategy.

The macronutrient calcium (Ca) analyzed by H3A plant organic acid extract was 11,683.55 lbs/ac on the twice-over strategy, 6824.79 lbs/ac on the seasonlong strategy, and 6464.49 lbs/ac on the nongrazed strategy (table 48). Calcium on the twice-over strategy was 80.7% greater than that on the nongrazed strategy, and was 71.2% greater than that on the seasonlong strategy. Calcium on the seasonlong strategy was 5.6% greater than that on the nongrazed strategy.

The macronutrient magnesium (Mg) analyzed by H3A plant organic acid extract was 2971.88 lbs/ac on the twice-over strategy, 1686.62 lbs/ac on the seasonlong strategy, and 1491.25 lbs/ac on the nongrazed strategy (table 48). Magnesium on the twice-over strategy was 99.3% greater than that on the nongrazed strategy, and was 76.2% greater than that on the seasonlong strategy. Magnesium on the seasonlong strategy was 13.1% greater than that on the nongrazed strategy.

The macronutrient sulfur (S) analyzed by H3A plant organic acid extract was 68.94 lbs/ac on the twice-over strategy, 34.68 lbs/ac on the seasonlong strategy, and 32.24 lbs/ac on the nongrazed strategy (table 48). Sulfur on the twice-over strategy was 113.8% greater than that on the nongrazed strategy, and was 98.8% greater than that on the seasonlong strategy. Sulfur on the seasonlong strategy was 7.6% greater than that on the nongrazed strategy.

The plant available macronutrients on the twice-over strategy were 82.7% greater than those on the nongrazed strategy, and was 66.5% greater than those on the seasonlong strategy. The plant available macronutrients on the seasonlong strategy were only 10.1% greater than those on the nongrazed strategy.

Sodium (Na) is not an essential element for plants and has the potential to result in sodic affected soils. Sodium analyzed by H3A plant organic acid extract was 220.26 lbs/ac on the twice-over strategy, 150.52 lbs/ac on the seasonlong strategy, and 171.73 lbs/ac on the nongrazed strategy (table 48). Sodium on the twice-over strategy was 28.3% greater than that on the nongrazed strategy, and was 46.3% greater than that on the seasonlong strategy. The twice-over strategy had 108.09 lbs/ac of increased sodium at the 12-24 inch soil depth which also had an elevated pH of 8.15, moderately alkaline, and an electrical conductivity of 0.3 mmhos/cm, low, indicating that at these levels, the sodium is not much of a problem. Sodium on the seasonlong strategy was 12.4% lower than that on the nongrazed strategy.

The micronutrient manganese (Mn) analyzed by H3A plant organic acid extract was 49.01 lbs/ac on the twice-over strategy, 24.60 lbs/ac on the seasonlong strategy, and 16.74 lbs/ac on the nongrazed strategy (table 49). Manganese on the twice-over strategy was 192.8% greater than that on the nongrazed strategy, and was 99.2% greater than that on the seasonlong strategy. Manganese on the seasonlong strategy was 47.0% greater than that on the nongrazed strategy.

The micronutrient copper (Cu) analyzed by H3A plant organic acid extract was 1.18 lbs/ac on the twice-over strategy, 0.81 lbs/ac on the seasonlong strategy, and 0.64 lbs/ac on the nongrazed strategy (table 49). Copper on the twice-over strategy was 84.4% greater than that on the nongrazed strategy, and was 45.7% greater than that on the seasonlong strategy. Copper on the seasonlong strategy was 26.6% greater than that on the nongrazed strategy.

The micronutrient iron (Fe) analyzed by H3A plant organic acid extract was 923.92 lbs/ac on the nongrazed strategy, 730.31 lbs/ac on the seasonlong strategy, and 581.80 lbs/ac on the twice-over strategy (table 49). Iron on the nongrazed strategy was 58.8% greater than that on the twice-over strategy, and was 26.5% greater than that on the seasonlong strategy. Iron on the seasonlong strategy was 25.5% greater than that on the twice-over strategy.

The micronutrient zinc (Zn) analyzed by H3A plant organic acid extract was 3.07 lbs/ac on the seasonlong strategy, 2.31 lbs/ac on the nongrazed strategy, and 1.75 lbs/ac on the twice-over strategy (table 49). Zinc on the seasonlong strategy was 75.4% greater than that on the twice-over strategy, and was 32.9% greater than that on the nongrazed strategy. Zinc on the nongrazed strategy was 32.0% greater than that on the twice-over strategy.

Manganese and Copper had the greatest plant availability on the twice-over strategy and the lowest plant availability on the nongrazed strategy. Iron had the greatest plant availability on the nongrazed strategy, zinc had the greatest plant availability on the seasonlong strategy and both iron and zinc had the lowest plant availability on the twice-over strategy.

Aluminum is not an essential element for either plants or animals. Aluminum ions at high concentrations can bond with enough hydroxyl ions removing the hydroxyl ions from solution moving the soil pH towards acidity. Aluminum (Al) analyzed by H3A plant organic acid extract was 1969.17 lbs/ac on the nongrazed strategy, 1656.79 lbs/ac on the seasonlong strategy, and 1488.81 lbs/ac on the twice-over strategy (table 49). Aluminum on the nongrazed strategy was 32.3% greater than that on the twice-over strategy, and was 18.9% greater than that on the seasonlong strategy. Aluminum on the seasonlong strategy was 11.3% greater than that on the twice-over strategy. The pH level on all of the management strategies at all of the soil depths were neutral or moderately alkaline and no pH level was acid (table 46).

The quantities of macronutrients and micronutrients analyzed by H3A plant organic acid extract consist of the small portion that is readily available to plants from cropland soils by secreted organic acids unassisted by soil microbes. In grassland soils where symbiotic soil microbes are surrounding native grass plant active roots, the quantities of readily available macronutrients and micronutrients would be expected to be much greater than the amounts analyzed by H3A plant organic acid extract techniques.

Summary of Results

The Haney Soil Health Test analyzes numerous chemical and biological components of soil to quantitatively evaluate soil health. Most of these components were greater in the soils managed with the twice-over strategy, while most of these components were lower in the soils managed with the long-term nongrazed strategy, and the components in soils managed with the traditional seasonlong strategy were usually in between.

The nongrazed strategy had the lowest microbial activity and the lowest microbe biomass. The twice-over strategy had the greatest microbial activity at 16.0% greater than that on the seasonlong strategy, and had similar but 9.8% lower microbial biomass than that on the seasonlong strategy. The soil microorganisms on the twice-over strategy appear to have transformed through some selection process resulting in fewer microorganisms with a lower microbial biomass that can maintain a greater activity level and perform greater quantities of biogeochemical processes.

The nongrazed strategy had the lowest quantity of soil organic matter (SOM) that was 32.7% lower than that on the seasonlong strategy and was 37.2% lower than that on the twice-over strategy. The twice-over strategy had the greatest SOM that was 7.4% greater than that on the seasonlong strategy. The nongrazed strategy had the lowest water extractable organic carbon and organic nitrogen that was 8.5% lower and 5.6% lower than the WEOC and WEON on the seasonlong strategy, respectively. The twice-over strategy had the greatest WEOC and WEON that was 35.0% greater and 28.2% greater than the WEOC and WEON on the seasonlong strategy, respectively.

The nongrazed strategy had the lowest quantity of total inorganic nitrogen that was 20.8% lower than that on the seasonlong strategy and had the lowest quantities of nitrate and ammonium that were 25.0% lower and 19.1% lower than those on the seasonlong strategy, respectively. The twice-over strategy had the greatest quantity of total inorganic nitrogen that was 45.7% greater than that on the seasonlong strategy and had the greatest quantities of nitrate and ammonium that were 29.4% greater and 52.1% greater than those on the seasonlong strategy, respectively.

The seasonlong strategy had the lowest quantities of total phosphorus and inorganic phosphorus that were 8.4% lower and 21.2% lower than those on the nongrazed strategy, respectively, and the twice-over strategy had the lowest quantities of organic phosphorus that was 2.9% lower than that on the nongrazed strategy. The twice-over strategy had the greatest quantities of total phosphorus and inorganic phosphorus that were 8.9% greater and 19.4% greater than those on the nongrazed strategy, respectively, and the seasonlong strategy had the greatest quantity of organic phosphorus that was 6.1% greater than that on the nongrazed strategy.

The nongrazed strategy had the lowest quantities of the macronutrients, potassium, calcium, magnesium, and sulfur, that were 12.4% lower, 5.3% lower, 11.6% lower, and 7.0% lower, than those on the seasonlong strategy, respectively. The twice-over strategy had the greatest quantities of the macronutrients, potassium, calcium, magnesium, and sulfur, that were 19.9% greater, 71.2% greater, 76.2% greater, and 98.8% greater, than those on the seasonlong strategy, respectively.

The nongrazed strategy had the lowest quantities of the micronutrients, manganese and copper, that were 32.0% lower and 21.0% lower, than those on the seasonlong strategy, respectively. The twice-over strategy had the greatest quantities of the micronutrients, manganese and copper, that were 99.2% greater and 45.7% greater, than those on the seasonlong strategy, respectively.

The twice-over strategy had the lowest quantities of the micronutrient, iron, that was 20.3% lower than that on the seasonlong strategy, and had the lowest quantity of the micronutrient, zinc, that was 24.2% lower than that on the nongrazed strategy. The nongrazed strategy had the greatest quantity of the micronutrient, iron, that was 26.5% greater than that on the seasonlong strategy. The seasonlong strategy had the greatest quantity of the micronutrient, zinc, that was 32.9% greater than that on the nongrazed strategy,

Discussion

The Haney Soil Health Test was designed to evaluate soil health of mixed cropland soils. The Haney Soil Health data sorted the intact grassland soils of the three management strategies into the same order as the wet chemistry data. The soil health number for the twice-over strategy was 18% greater than that for the seasonlong strategy and 48% greater than that for the nongrazed strategy. The soil health number for the seasonlong strategy was 25% greater than that for the nongrazed strategy. The pounds per acre of available nitrogen, phosphorus, and potassium on the twice-over strategy was 35%, 28%, and 22% greater than those on the seasonlong strategy, and was 71%, 12%, and 58% greater than those on the nongrazed strategy, respectively. The pounds per acre of available nitrogen, and potassium on the seasonlong strategy was 26% and 29% greater than those on the nongrazed strategy, respectively, and the pounds per acre of available phosphorus on the nongrazed strategy was 14% greater than that on the seasonlong strategy.

The soil carbon dioxide respiration test measures soil microbe activity braking down the available carbohydrates in the soil organic matter. The microbe activity on the twice-over strategy was 16% greater than that on the seasonlong strategy and was 68% greater than that on the nongrazed strategy. The microbe activity on the seasonlong strategy was 45% greater than that on the nongrazed strategy. The solvita test does not measure microbe activity in the rhizosphere resulting for exudation of surplus grass plant fixed carbon energy.

The Phospholipid Fatty Acid (PLFA) analysis measures the quantity of the different biomarkers of phospholipid fatty acids representing the various functional groups of soil microbes. Except about 40% of the microbes in grassland soils are unknown. The twice-over strategy had greater biomass of fungi and protozoa than the other two management strategies but had lower bacteria biomass and total microbe biomass than those on the seasonlong strategy.

The quantities of available essential elements were measured by water extraction or by H3A plant organic acid extraction which evaluate the amount of each essential element available in the soil that could be obtained by plant processes alone without assistance from soil microbes. The quantities of available essential elements were greatest on the twice-over strategy, second on the seasonlong strategy, and lowest on the nongrazed strategy for all essential elements except phosphorus, iron, and zinc.

The mixed cropland soils contain only free living edaphosphere microbes. The plant beneficial microbes congregate near annual crop plant roots that leak substance that microbes can use for energy. The plant beneficial microbes may assist the annual plants by procuring some essential elements, but probably only a small portion of their needs.

The intact grassland soils with perennial grasses contain symbiotic rhizosphere microbes that vary in biomass depending on the quantity of plant surplus carbon energy exudated into the rhizosphere. Perennial grasses on the nongrazed strategy would contain the lowest microbe biomass that receive carbon energy at the plant leakage rate. The microbe biomass would be a little greater on the seasonlong strategy than that on the nongrazed strategy because the microbes would receive the regular leakage amount plus some exudated plant carbon energy unintentionally released through cattle grazing. The microbe biomass would be greatest on the twice-over strategy as a result of coordinated partially defoliated lead tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage causing large quantities of surplus carbon energy to be exudated through the grass roots into the rhizosphere available for microbe biomass to increase to levels that can mineralize greater than 100 lbs/ac of mineral nitrogen and that can reestablish the full functionality of all ecosystem biogeochemical processes.

Table 45. Soil microbe biomass (ng/g) by phospholipid fatty acid (PLFA) analysis at soil depths to 24 in deep, June and July, 2016-2018.

Soil Microbes		Soil Depth inches	Management Treatments Nongrazed 34 -36 yrs.	 Seasonlong 30-32 yrs	 Twice-over 34-36 yrs.
Microbial Activity CO_2-C released/24 hr					
	lbs/ac	0-6	434.13	666.41	729.49
		6-12	216.15	258.94	357.35
		12-24	102.25	165.68	178.53
		0-24	752.53	1091.02	1265.37
Total Microbes					
	ng/g	0-6	4240.39	5192.99	4354.85
		6-12	1554.22	1852.45	2120.24
		12-24	1229.44	1837.49	1539.22
		0-24	7024.04	8882.92	8014.30
Total Bacteria					
	ng/g	0-6	2149.59	2607.37	2166.11
		6-12	641.89	825.49	1002.58
		12-24	496.93	773.37	626.22
		0-24	3288.40	4206.22	3794.91
Total Fungi					
	ng/g	0-6	575.21	670.01	583.00
		6-12	128.52	170.16	315.15
		12-24	110.96	200.39	248.26
		0-24	814.69	1040.55	1146.40
Protozoa					
	ng/g	0-6	27.38	31.73	29.30
		6-12	4.78	4.73	10.79
		12-24	0.00	5.02	1.98
		0-24	32.16	41.47	42.07
Unknown					
	ng/g	0-6	1488.41	1896.41	1577.88
		6-12	779.08	852.29	791.72
		12-24	620.78	858.73	662.77
		0-24	2888.26	3607.42	3032.37

Table 46. Essential element weight (lbs/ac) by water extract at soil depths to 24 in deep, June and July, 2016-2018.

		Management Treatments		
Essential Elements	Soil Depth inches	Nongrazed 34 -36 yrs.	Seasonlong 30-32 yrs	Twice-over 34-36 yrs.
Soil pH				
	0-6	7.00	6.81	6.83
	6-12	6.94	6.79	7.14
	12-24	7.22	7.34	8.15
Soluble Salts				
mmho/cm	0-6	0.15	0.18	0.23
	6-12	0.12	0.11	0.20
	12-24	0.14	0.19	0.30
Organic Matter				
%	0-6	3.38	6.00	5.52
	6-12	2.24	2.85	3.54
	12-24	1.47	1.99	2.29
Total Organic Carbon				
lbs/ac	0-6	951.20	1148.55	1511.90
	6-12	792.93	829.10	1258.47
	12-24	595.52	579.75	683.35
	0-24	2339.65	2557.40	3453.72
Total Nitrogen				
lbs/ac	0-6	81.66	98.66	136.56
	6-12	59.85	62.61	95.75
	12-24	43.54	37.57	37.70
	0-24	185.05	198.84	270.00
Organic Nitrogen				
lbs/ac	0-6	69.64	81.48	104.44
	6-12	51.70	55.78	79.60
	12-24	39.16	32.79	33.91
	0-24	160.50	170.05	217.95

Table 47. Essential element weight (lbs/ac) by H3A (plant organic acids) extract at soil depths to 24 in deep, June and July, 2016-2018.

Essential Elements		Soil Depth inches	Management Treatments Nongrazed 34 -36 yrs.	Seasonlong 30-32 yrs	Twice-over 34-36 yrs.
Inorganic Nitrogen					
	lbs/ac	0-6	15.93	23.37	31.63
		6-12	10.42	10.24	22.03
		12-24	5.68	6.85	6.14
		0-24	32.04	40.46	59.79
Nitrate					
	lbs/ac	0-6	5.52	8.01	10.02
		6-12	2.18	2.12	2.96
		12-24	0.84	1.25	1.75
		0-24	8.54	11.38	14.73
Ammonium					
	lbs/ac	0-6	10.50	15.40	21.60
		6-12	8.24	8.14	18.41
		12-24	4.84	5.62	4.34
		0-24	23.58	29.16	44.35
Total Phosphorus					
	lbs/ac	0-6	26.10	32.90	40.52
		6-12	25.02	27.19	47.05
		12-24	34.53	17.13	3.27
		0-24	85.65	77.23	90.84
Organic Phosphorus					
	lbs/ac	0-6	15.45	19.00	20.25
		6-12	13.25	14.43	15.91
		12-24	10.96	8.62	2.34
		0-24	39.65	42.05	38.50
Inorganic Phosphorus					
	lbs/ac	0-6	10.28	14.01	20.32
		6-12	11.20	12.62	31.54
		12-24	23.20	8.58	1.49
		0-24	44.68	35.22	53.35

Table 48. Essential element weight (lbs/ac) by H3A (plant organic acids) extract at soil depths to 24 in deep, June and July, 2016-2018.

Essential Elements		Soil Depth inches	Nongrazed 34 -36 yrs.	Seasonlong 30-32 yrs	Twice-over 34-36 yrs.
			Management Treatments		
Potassium (K)					
	lbs/ac	0-6	485.93	518.02	673.50
		6-12	352.96	387.22	486.02
		12-24	194.16	274.10	254.98
		0-24	1033.05	1179.34	1414.50
Calcium (Ca)					
	lbs/ac	0-6	1588.32	1775.95	1892.87
		6-12	1415.65	1496.95	1965.21
		12-24	3460.52	3551.89	7825.47
		0-24	6464.49	6824.79	11683.55
Magnesium (Mg)					
	lbs/ac	0-6	473.15	547.39	738.68
		6-12	441.75	505.78	739.10
		12-24	576.35	633.45	1494.11
		0-24	1491.25	1686.62	2971.88
Sodium (Na)					
	lbs/ac	0-6	41.61	48.13	52.62
		6-12	47.73	46.91	59.56
		12-24	82.40	55.48	108.09
		0-24	171.73	150.52	220.26
Sulfur (S)					
	lbs/ac	0-6	12.65	13.87	20.81
		6-12	11.02	11.42	22.03
		12-24	8.57	9.39	26.11
		0-24	32.24	34.68	68.94

Table 49. Essential element weight (lbs/ac) by H3A (plant organic acids) extract at soil depths to 24 in deep, June and July, 2016- 2018.

			Management Treatments		
Essential Elements Microminerals		Soil Depth inches	Nongrazed 34 -36 yrs.	Seasonlong 30-32 yrs	Twice-over 34-36 yrs.
Iron (Fe)					
	lbs/ac	0-6	329.92	261.84	297.73
		6-12	375.02	302.08	228.45
		12-24	218.98	166.39	55.63
		0-24	923.92	730.31	581.80
Manganese (Mn)					
	lbs/ac	0-6	8.61	13.99	18.48
		6-12	4.29	6.24	29.62
		12-24	3.84	4.37	0.91
		0-24	16.74	24.60	49.01
Zinc (Zn)					
	lbs/ac	0-6	1.33	2.20	1.26
		6-12	0.71	0.65	0.47
		12-24	0.27	0.23	0.03
		0-24	2.31	3.07	1.75
Copper (Cu)					
	lbs/ac	0-6	0.19	0.20	0.48
		6-12	0.21	0.34	0.64
		12-24	0.25	0.28	0.06
		0-24	0.64	0.81	1.18
Aluminum (Al)					
	lbs/ac	0-6	601.31	505.54	615.90
		6-12	801.01	674.06	668.69
		12-24	566.85	477.19	204.22
		0-24	1969.17	1656.79	1488.81

E. Summary of the Indispensable Rhizosphere Organisms

Grassland ecosystems of the Northern Mixed Grass Prairie degrade with the removal of large grazing graminivores. The traditional purpose of the nongrazed treatment that removes grazing defoliation by graminivores with the intention of "resting" the grazingland ecosystem as a restoration management practice developed from long-time concepts that do not go deeper than the soil surface. This misguided practice was based on a naive assumption that the observed vigor depletion of grassland communities was caused by livestock grazing, rather than being caused by poor management of livestock grazing, and that the lost vigor of the grass plants could be restored by resting. Ironically, removal of livestock grazing does not rest an ecosystem like the rest experienced by a hard working human swinging in a hammock; the grass plants are debilitated and the soil microorganisms are devitalized like the enfeeblement of an elderly person sitting alone in a rocking chair. Nongrazed native grasses provide simple carbohydrate energy to soil microbes only at the typical low leakage rate resulting in a small biomass of microorganisms. The ecosystem biogeochemical processes function at increasingly regressive degrees below potential levels each growing season without grazing. Soon after the first ecosystem process fails to function properly, the other belowground processes and mechanisms begin to deteriorate. The native grass live root biomass decreases (Whitman 1974), the physiological mechanisms within grass plants diminish, the ecosystem biogeochemical processes decline rapidly, and the competitiveness of grass plant resource uptake deteriorate (Manske 2011b).

The reduction of live root surface area causes a decrease in active root length for interaction with symbiotic rhizosphere organisms and causes a decrease in absorption of water and essential nutrients from the soil. Reduction of active root biomass and diminishment of grass plant health vigor results 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 and Wilson 2000, Peltzer and Kochy 2001). The loss of active root length is a contributing factor in the reduction of rhizosphere biomass. The primary cause for the reduction in rhizosphere biomass was, however, the great reduction in the quantity of carbohydrates exuded from the grass roots into the rhizosphere zone. The lack of partial defoliation by grazing graminivores directly prevented the exudation of large quantities of carbon energy from grass plants into the rhizosphere. The resulting small biomass of rhizosphere organisms only can mineralize 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 causes reductions in native grass herbage biomass production (Wight and Black 1972, 1979) and causes decreases in native grass density (basal cover). As degradation continues, numerous bare spaces between native grass plants are created in the plant communities. The open spaces are ideal habitat for growth of opportunistic introduced domesticated grass species, weedy forbs, and shrubs. The composition of grass species changes with decreases in the desirable native species and increases in the less desirable and undesirable species.

Standing dead leaves accumulate (Brand and Goetz 1986) as ecosystem deterioration progresses. Grass plants produce double the quantity of leaf biomass that is needed for normal plant growth and maintenance (Crider 1955, Coyne et al. 1995). When the extra leaf biomass is not removed by grazing annually, that extra biomass becomes detrimental. The accumulation of live and standing dead leaves reduce light penetration greatly. This reduction of sunlight to native grasses causes 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 do not make contact with soil preventing decomposition through microbial activity and causing litter to build up into a thick mulch layer. The thick mulch modifies soil temperature, inhibits water infiltration, and ties up carbon and nitrogen (Wright and Bailey 1982, Manske 2000, 2011b). Native grasses are 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 introduced grasses, weedy forbs, and woody shrubs is the visible symptom of ecosystem degradation; the fundamental degradation of the ecosystem is the reduction of rhizosphere biomass, the reduction of biogeochemical processes, the reduction of available mineral nitrogen below 100 lbs/ac, the reduction in availability of all the other essential elements. The degree of the aboveground plant species deterioration lags behind the degree of degradation of the belowground ecosystem biogeochemical processes and mechanisms

(Manske 2011b). Removal of cattle grazing does not promote development of stable climax plant communities and does not preserve prairie grasslands in perpetuity. Grassland communities deprived of large grazing graminivores decline steadily into unhealthy dysfunctional ecosystems with severe reductions of native grasses, considerable decreases of desirable forbs, enormous increases of introduced domesticated grasses, remarkable increases of woody shrubs and trees, and excessive increases of standing dead and litter.

Intrusive seedlings can only become established in a grassland after the ecosystem has been degraded by poor management practices. Seedlings of trees, shrubs, weedy forbs, and introduced grasses cannot become established in grassland ecosystems containing healthy grass with full nutrient resource uptake competitiveness (Peltzer and Kochy 2001). The existence of woody plant components in grasslands is not an ecologically beneficial relationship as woody plants and grasses are adversarial inhibitive competitors. Grasses and woody plants compete for sunlight, mineral nitrogen, other essential elements, and soil water. Fire in grasslands cannot prevent the invasion of, or cause the removal of, shrubs and trees that are able to reproduce by vegetative secondary suckers (Wright and Bailey 1982, Manske 2006a, b). Almost all deciduous woody plants can reproduce vegetatively, except big sagebrush (Artemisia tridentata) (Manske 2014d).

Burning cannot restore degraded grassland ecosystems and fire does not improve grassland ecosystems biologically or ecologically. Burning treatments do not increase water infiltration or soil water holding capacity. Burning treatments do not increase endomycorrhizal fungal colonization. Burning treatments do not increase rhizosphere microbe biomass and activity levels. Burning treatments do not increase mineralization of organic nitrogen into inorganic nitrogen. Burning treatments do not increase total herbage biomass production. Burning treatments do not restore functionality to degraded grassland ecosystems. The fundamental problems of weak nutrient resource uptake, reduced water use efficiency, nonfunctional compensatory physiological mechanisms and vegetative reproduction by tillering remain within the plants and diminished biogeochemical processes remain in the degraded ecosystems following repeated burning treatments. None of the biological, physiological, or asexual mechanisms within grass plants and none of the rhizosphere microbes or the biogeochemical processes they perform are activated by burning treatments (Manske 2007a, 2011a, 2014d, 2018).

Burning grasslands exacerbates ecosystem degradation. When the losses of essential elements are greater than the quantity of captured major essential elements, the result is expanded degradation of the ecosystem (McGill and Cole 1981). Almost all of the essential elements in the aboveground herbage are volatilized when grasslands burn, and there are no active processes in burned grasslands to recapture the lost major essential elements. When burning occurs during dry soil periods, some of the belowground essential elements are also lost (Russelle 1992). Burning grasslands does not restore degraded ecosystems. Degraded grasslands continue to have the same basic problems following the repeated prescribed burning regime, and when the burning sequence stops, the undesirable replacement plants return to dominate the communities (Manske 2018). The presence of periodic fire does not prove that grassland ecosystems need or are caused by fire (Heady 1975).

All of the biological and ecological problems found on rangeland ecosystems are the result of deficiencies in the amount of available mineral nitrogen below 100 lbs/ac in the soil. The primary objective to correct any and all of these problems is to elevate the rhizosphere microorganism biomass to a level that can mineralize adequate quantities of organic nitrogen so that the quantity of available mineral nitrogen occurs at or above the threshold rate of 100 lbs/ac (112 kg/ha).

The rhizosphere microorganism biomass and biogeochemical activity are limited by the access to energy from simple carbon chains. The small quantities of energy available from short chain carbohydrates in root leakage or in recent deposition of fresh organic plant material are inadequate to support a large rhizosphere biomass. The only source of large quantities of energy from simple carbon chains is the surplus carbon fixed through photosynthesis during grass plant vegetative growth stages. This surplus carbon energy is not automatically released to soil microbes. The grass plant carbon-nitrogen ratio must be disrupted by removing greater amounts of nitrogen than carbon. The grazing periods of the twice-over rotation strategy are coordinated with grass tiller phenological growth and development. Partial defoliation by grazing graminivores that removes 25% to 33% of the aboveground leaf weight on about 60% to 80% of the lead grass tillers at vegetative growth stages between the three and a half new leaf stage and the flower stage removes greater quantities of nitrogen as crude protein than the quantities of removed carbon which intentionally causes large quantities of grass leaf surplus simple carbohydrates to be exudated through the roots into the rhizosphere. This large increase in available simple carbon energy increases the microorganism biomass in the rhizosphere and elevates microbe biogeochemical activity resulting in great quantities of mineral nitrogen and other essential elements to become available to native grass species.

Rhizosphere microbes with low biomass from 104 kg/m^3 to 171 kg/m^3 can mineralize only 26.3 kg/ha to 65.2 kg/ha (23.5 lbs/ac to 58.2 lbs/ac) of mineral nitrogen. Rhizosphere microbes with high biomass from 214 kg/m^3 to 406 kg/m^3 can mineralize 111.3 kg/ha to 176.3 kg/ha (99.4 lbs/ac to 157.4 lbs/ac) of mineral nitrogen.

Grass plants have four major internal growth mechanisms: compensatory physiological mechanisms, asexual mechanisms for vegetative reproduction by tillering, competitive nutrient resource uptake mechanisms, and precipitation (water) use efficiency mechanisms. A threshold quantity of 112 kg/ha (100 lbs/ac) of mineral nitrogen must be available before these important growth mechanisms can be fully activated.

Full activation of the compensatory physiological mechanisms within grass plants accelerates growth rates of replacement leaves and shoots, increase photosynthetic capacity of remaining mature leaves that increase the quantity of available fixed carbon, and increases restoration of biological and physiological processes enabling rapid and complete recovery of partially defoliated grass tillers. Replacement grass biomass is about 140% of the grass biomass removed by grazing.

Full activation of the asexual mechanisms for vegetative reproduction by tillering 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 through the grazing period.

Full activation of the nutrient resource uptake mechanisms increases root absorption of soil water and the major and minor essential element, improves the robustness of grass growth and development, increases competitiveness of healthy grasses, and increases suppression of undesirable grass, weedy forb, and shrub seedlings or rhizomes from encroachment and establishment within grassland communities.

Full activation of the precipitation (water) use efficiency mechanisms increases herbage biomass production 50.4% per inch of rainfall received, and greatly reduces the detrimental effects to grass herbage production during water deficiency periods and from drought conditions.

Grass plants require 17 major and minor essential elements to execute the physiological functions needed for life of which 13 essential elements, the 4 major essential elements, the 5 macrominerals, and 4 of the 8 microminerals, require biogeochemical processes performed by soil microbes to transform these essential elements into forms that can be used by grass plants. The twice-over rotation strategy has been shown to contain the largest quantity of soil organic matter (SOM) with the highest annual mean accumulation rate at 8408 lbs/ac/yr, which is probably the closest quantitative value measurable for net primary productivity (NPP) of an ecosystem. The soils managed with the twice-over strategy had the greatest quantities of organic carbon, organic nitrogen, and total phosphorus, the soils contained the greatest quantities of available inorganic nitrogen (both nitrate and ammonium), inorganic phosphorus, and the greatest quantities of available forms of potassium, calcium, magnesium, sulfur, manganese, and copper, with adequate quantities of available forms of iron and zinc.

A large biomass of rhizosphere microorganisms can perform all of the grassland ecosystem biogeochemical processes that renew nutrient flow activities in the intact soil. Biogeochemical processes transform stored essential elements from organic forms into plant-usable inorganic forms. Biogeochemical processes also capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen, with assistance from active live plants, and transform the captured major essential elements into storage as organic forms for later use. And the biogeochemical processes also decompose complex unusable organic material into compounds and then into reusable essential elements (Manske 2018).

The quantity of herbage biomass production and the nutritional quality of the herbage and the quantity of cow and calf weight gains on rangeland pastures are directly related to the biomass of the rhizosphere microorganisms. Positive and negative oscillations in plant species composition and herbage production of the aboveground plant communities follow the changes in belowground rhizosphere microbe biomass and their biogeochemical activity. When the rhizosphere microorganism biomass and activity is large enough to mineralize 100 lbs/ac or greater of available mineral nitrogen, the desirable native grass species increase, with increases in density and herbage biomass, and the less desirable and undesirable plant species decrease. The plant species composition moves in the opposite direction when the rhizosphere microorganism biomass and activity mineralize less than 100 lbs/ac of mineral nitrogen. The typical low grass herbage biomass, the low nutritional quality of forage after July, and the low calf weight gains on rangeland pastures managed with traditional management practices results from deficient quantities of available mineral nitrogen because the biomass of the rhizosphere microorganisms is too low to mineralize adequate quantities of mineral nitrogen to fulfill the required threshold level of 100 lbs/ac.

The rhizosphere microorganisms are the renewable part of grassland natural resources. These microorganisms are the hugely underrated indispensable biotic component that are the impelling force driving grassland ecosystem functions.

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Domesticated Graminivores:
An Indispensable Biotic Component of the Northern Mixed Grass Prairie

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

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component part and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains. The introduction to this study can be found in report DREC 16-1093 (Manske 2016).

Grass vegetation, rhizosphere organisms, and domesticated graminivores are indispensable biotic components of a functional rangeland ecosystem. Grazing graminivores depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short carbon chain energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing graminivores. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing graminivores on which they depend.

The three indispensable biotic components of rangeland ecosystems: Grass Vegetation, Rhizosphere Organisms, and Domesticated Graminivores will each be quantitatively described in separate companion reports. This report will provide quantitative knowledge of grazing domesticated graminivores as indispensable biotic components of grassland ecosystems.

Indispensable Graminivores

Grazing large graminivores on a fully functional grassland ecosystem can be perpetually sustainable with biologically effective management that activates the ecosystem biogeochemical processes and the grass plant physiological mechanisms to function at potential levels. When these processes and mechanisms function above threshold levels, capture and replenishment of input essential elements occurs at greater quantities than the amount of output essential elements. Soil organisms and grass plants use the essential elements in the inorganic form to synthesize vital organic compounds of carbohydrates, proteins, and nucleic acids. Grass plants produce double the quantity of leaf biomass than needed for normal plant growth and maintenance (Crider 1955, Coyne et al. 1995). All of the aboveground herbage biomass produced by perennial grasses in a growing season represents about 33% of the total biomass produced. About 67% of the annual perennial grass biomass is produced belowground. About 50% of the aboveground biomass is expendable by the grass plant (Crider 1955). About half of the expendable leaf material is removed as senescent leaves that are broken from the plant and fall to the ground as litter, or removed as leaf material by wildlife, grasshoppers, and other small animals. About half of the expendable leaf material, or 25% of the aboveground grass biomass can be consumed by grazing graminivores (Manske 2012a).

Graminivores grazing grass plants acquire energy, protein, macrominerals, and microminerals from the forage they consume. Perennial grass leaf material consists of both digestible nutrients and nondigestible plant structural components. Adequate quantities of crude protein and energy are available to the graminivores during early June through mid October from the growing forage grass plants on fully functional ecosystems. About 15% of the nutrients contained in the consumed grass leaf material is extracted by stocker heifers and steers and retained for growth. About 30% of the nutrients contained in the consumed grass leaf material is extracted by lactating cows, with a portion retained by the cow for production, and the remainder of the extracted nutrients passed on the her calf for growth (Russelle 1992, Gibson 2009).

All of the nondigestible dry matter and most of the nutrients consumed by grazing graminivores are deposited on the ground as manure in a couple of days. Most of the consumed nutrients extracted and used by graminivores for maintenance are returned to the ecosystem in the feces and urine. None of the herbage biomass dry matter produced during a growing season is removed by graminivores from the grassland ecosystem. All of the essential elements contained in the belowground biomass and contained in the nonconsumed aboveground biomass stay in the ecosystem. Nearly all of the essential elements used in the annual production of grass herbage biomass and soil organism biomass are retained and recycled in the ecosystem.

Some essential elements are lost or removed from the ecosystem as annual output. The metabolic process of respiration of soil organisms, grass plants, graminivores, and other fauna results in a loss of some essential elements as carbon dioxide, water vapor, and heat energy. Some essential elements are removed from the ecosystem as weight biomass produced by insects and wildlife. The essential elements transferred from grass plants to grazing graminivores and used for growth are removed from the ecosystem (Gibson 2009). If the grassland ecosystem is burned, almost all of the essential elements in the aboveground herbage are volatized, and if the soil is dry, some of the belowground essential elements are also lost (Russelle 1992).

Grassland ecosystems degrade when the losses of essential elements is greater than the capture of replacement essential elements. Conversely, grassland ecosystems aggrade when the capture of essential elements is greater than the losses (McGill and Cole 1981). A large biomass of soil microbes and healthy grass plants is required to aggrade grassland ecosystems (Coleman et al. 1983, Schimel, Coleman, and Horton 1985, Cheng and Johnson 1998). When the ecosystem biogeochemical processes and the grass plant physiological mechanisms are functioning at potential levels, a grazed grassland ecosystem is perpetually sustainable (Manske 2013).

1983-2005 Study of Graminivore Weight Performance

Management Treatments

A 23 year study separated into two sections, with the first portion from 1983 to 1994 and the second portion from 1995 to 2005, evaluated cow and calf weight performance on spring, summer, and fall pastures managed by two distinctly different concepts. The traditional concept managed the land for its use as forage for livestock. The biologically effective concept managed the land as an ecosystem that considers the biological requirements of the grass plants, soil microbes, and the livestock.

Spring Complementary Pastures

The traditional spring complementary pasture was unfertilized crested wheatgrass. During 1983 to 1988, the livestock managed by the traditional concept grazed unfertilized crested wheatgrass pastures during May to mid June, however, weight performance data were not collected. During 1989 to 1994, cow and calf pairs grazed one unfertilized pasture of 18 acres (replicated two times) at 2.45 ac/AUM for 28 days (2.25 ac/AU) from mid May to mid June. During 1995 to 2005, cow and calf pairs grazed one unfertilized pasture of 15 acres (replicated three times) at 2.33 ac/AUM for 28 days (2.14 ac/AU) from early May to early June (Appendix tables 6-10).

The biologically effective spring complementary pasture was crested wheatgrass. During 1983 to 1994, cow and calf pairs grazed one pasture of 13 ac fertilized with 50 lbs N/ac during early April (replicated two times) at 0.85 ac/AUM for 21 days from mid May to early June. During 1995 to 2005, cow and calf pairs grazed one unfertilized pasture of 26.5 acres split into equal halves with each portion used for 2 alternating 7 day periods in a switchback plan (replicated two times) at 1.25 ac/AUM for 28 days from early May to early June (Appendix tables 1-5).

Summer Pastures

The traditional summer pasture was native rangeland. During 1983 to 1987, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated two times) at 6 cows per 80 acres with 13.33 ac/AU for 134 days from mid June to late October. During 1988 to 1990 a dry period, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated three times) at 7 cows per 80 acres with 11.43 ac/AU for 85 days from mid June to mid September. During 1991 to 1994, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated two times) at 7 cows per 80 acres with 11.43 ac/AU for 127 days from mid June to late October. During 1995 to 1997, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated three times) at 7 cows per 80 acres with 11.43 ac/AU for 131 days from early June to mid October. During 1998 to 2001, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated three times) at 7 cows per 80 acres with 11.43 ac/AU for 134 days from early June to mid October. During 2002 to 2005, cow and calf pairs grazed one native rangeland pasture seasonlong (replicated two times) at 7 cows per 80 acres with 12.22 ac/AU for 135 days from early June to mid October (Appendix tables 16-20).

The biologically effective summer pastures were native rangeland. During 1983 to 1987, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.22 ac/AU for 138 days from early June to mid October. During 1988 to 1990 a dry period, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.22 ac/AU for 100 days from early June to mid September. During 1991 to 1994, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.22 ac/AU for 121 days from early June to early October. During 1995 to 1997, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.22 ac/AU for 130 days from early June to mid October. During 1998 to 2001, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.22 ac/AU for 131 days from early June to mid October. During 2002 to 2005, cow and calf pairs grazed three native rangeland pastures with twice-over rotation (replicated two times) at 8 cows per 80 acres with 10.59 ac/AU for 135 days from early June to mid October (Appendix tables 11-15).

Fall Complementary Pastures

The traditional fall complementary pasture was cropland aftermath consisting primarily of annual cereal residue of oat or barley stubble with some senescent grass on the headlands and waterways. During 1983 to 1998, cow and calf pairs grazed cereal residue forage (replicated two times) at 6.63 ac/AU for 30 days from mid October to mid November (Appendix tables 26-27).

The biologically effective fall complementary pastures were Altai wildrye and spring seeded winter cereal (fall or winter rye). During 1984 to 2002, cow and calf pairs grazed one pasture of Altai wildrye (replicated two times) at 1.39 ac/AU for 30 days from mid October to mid November (Appendix tables 21-23). During 2003 to 2005, cow and calf pairs grazed 4 pastures of spring seeded winter cereal with a fresh pasture made available every 7 to 8 days stocked at 0.47 ac/AU for 30 days from mid October to mid November (Appendix tables 24-25).

Domesticated Graminivores

Commercial cow-calf pairs were evaluated during this study. During 1983 to 1994, commercial Angus-Hereford cows with Charolais sired calves were used. Cows were assigned to separate herd pools for each grazing treatment. Before spring turn out, cow-calf pairs were sorted by cow age, and calf age with 50% steers and heifers. During 1995 to 2005, commercial crossbred cattle were used on all grazing treatments. Before spring turn out, cow-calf pairs were sorted by cow age, and calf age with 50% steers and heifers. Calves were born during March and early April with the average birth date of 16 March and the average birth weight of 95 pounds during the entire study period.

Precipitation

The precipitation in inches and percent of long-term mean for perennial plant growing season months, April to October, and growing season months with water deficiency conditions are reported in the study introduction (Manske 2016). The 12 year period of 1983 to 1994 had a total of 72 growing season months, 31 months (43.1%) had water deficiency conditions, 14.5 months (20.1%) had high precipitation greater than 125% of LTM, and 26.5 months (36.8%) had normal precipitation greater than 75% and less than 125% of LTM. The 11 year period of 1995 to 2005 had a total of 66 growing season months, 15.5 months (23.4%) had water deficiency conditions, 27.5 months (41.7%) had high precipitation greater than 125% of LTM, and 23.0 months (34.8%) had normal precipitation greater than 75% and less than 125% of LTM.

Procedure

Individual cows and calves were weighed on and off each treatment pasture, at 15-day intervals during the early portion of the grazing season from early May to mid July, and at 30-day intervals during the latter portion of the grazing season from mid July to mid November. Total accumulated weight gain per head, gain per day, and gain per acre were determined.

Pasture costs were determined using pasture rent value of $8.76 per acre calculated from the mean rent values of the 15 counties in southwestern North Dakota reported for 1993 and 1994 (ND Ag Statistics). Total pasture costs and costs per day were determined. Grazing cropland aftermath cost was determined to be $2.00 per acre.

Market value per pound of calf pasture accumulated live weight gain was determined from the low market value of $0.70 per pound occurring during 1993 and 1994.

Net returns per cow-calf pair were determined by subtracting pasture costs from calf pasture weight gain value. Net returns per acre were determined by dividing the net returns per cow-calf pair by the number of acres used per Animal Unit (AU) per production period.

One treatment of crested wheatgrass was fertilized annually with 50 pounds of nitrogen per acre at an average cost of $12.50 per acre used during 1983 to 1994. Land rent plus fertilizer cost was $21.26 per acre.

Results

At the start of this study, the consensus of the experienced range scientists of the Northern Mixed Grass Prairie was that grazing readiness of native rangeland started on 15 June based on the research by Campbell (1952) and Rogler et al. (1962), and as reported together by Manske (2008b). As a result, the grazing starting dates of the traditional seasonlong treatments during 1983 to 1994 were mid June. The first year (1983) of the biologically effective twice-over rotation treatment on native rangeland also started grazing in mid June. With some persuasion, for the purpose of new research, the grazing starting dates of the biologically effective twice-over rotation treatment were moved to early June during 1984 to 2005. The starting date of the spring turn out to the traditional crested wheatgrass complementary pastures was thought to be around mid May, based on decades of previous research, which was the starting date used during 1983 to 1994. The duration of the grazing period on crested wheatgrass complementary pastures was also still undetermined at that time. Moving the grazing start date of the crested wheatgrass complementary pastures from mid May to early May was not accomplished until after 1994. During 1995 to 2005, the grazing start date for crested wheatgrass pastures was early May and the grazing start date for native rangeland pastures was early June for both the management practices of the traditional and biologically effective concepts. Perennial grass tillers are physiologically capable of tolerating partial defoliation after they have developed 3.5 new leaves. The major native cool season grasses reach the 3.5 new leaf stage around early June. Crested wheatgrass tillers reach the 3.5 new leaf stage on 22 April but do not have adequate herbage weight until early May to start the grazing period. Perennial grass phenological growth stages are determined by the length of daylight and occur at the same time (plus or minus 1 or 2 days) year after year.

In the past, a great deal of emphasis has been given to the dry matter intake requirements of beef cattle. During lactation, a 1000 lb cow requires 24 lbs of dry matter per day, a 1200 lb cow requires 27 lbs, and a 1400 lb cow requires 30 lbs per day (NRC 1996). When these lactating cows are grazing, the dry matter allocation is increased 2 lbs/day for the 1000 lb cow, and 3 lbs/day for the 1200 lb and 1400 lb cows (Manske 2012b). However, none of the cow and calf weight gain while grazing grass forage comes from the ingested dry matter, the weight gain comes mainly from the quantity of energy and crude protein extracted from the dry matter carrier while it passes through the digestive system of the livestock. The energy content of grass forage usually does not decrease below the cows requirements during the growing season of the Northern Mixed Grass Prairie. The crude protein content of grass lead tillers decreases below the cows requirements during mid to late July. At this point, cows are unable to maintain weight gain and milk production. Weight gain decreases first, then the quantity of milk production decreases. When the cows lose weight, the milk production decreases greatly and calf weight gains drop below 2.50 lbs/day. The reduction of crude protein content of grass forage below the cows requirements in late July can be avoided by activation of sufficient quantities of vegetative tillers developed from axillary buds with partial defoliation by graminivores that removes 25% to 33% of the leaf material from grass lead tillers at phenological growth between the three and a half new leaf stage and the flower (anthesis) stage during early June to mid July, which prevents cow weight lose and milk production reduction between mid July and late September or mid October (Manske 1999, 2011).

Spring Complementary Pastures

Crested wheatgrass is an excellent spring (May) complementary pasture. Crested wheatgrass was introduced into North America from Eurasia during the early 1900's. Early leaf greenup starts in mid April. The tillers have three and a half new leaves around 22 April which is four to five weeks earlier than native cool season grasses. The quantity of available herbage weight is insufficient for grazing until 1 May and provides superior quality forage to the end of May or to the first couple of days in June. The crude protein content from early May to early June ranges from 19.0% to 12.1%. Cows with calves one month old on 1 May perform very well while grazing crested wheatgrass (Manske 2017b).

During 1983 to 1994, cow and calf weight performance on a crested wheatgrass pasture fertilized with 50 lbs N/ac stocked at 0.85 ac/AUM was evaluated (Appendix tables 1-5). During 1989 to 1994, cow and calf weight performance on a crested wheatgrass unfertilized pasture stocked at 2.45 ac/AUM was evaluated (Appendix tables 6-10). On the fertilized pasture, calf weight gain was 2.37 lbs per day, 78.82 lbs per acre, and accumulated weight was 66.83 lbs per head. Cow weight gain was 2.57 lbs per day, 92.81 lbs per acre, and accumulated weight gain was 50.87 lbs per head (table 1). On the unfertilized pasture, calf weight gain was 2.34 lbs per day, 28.08 lbs per acre, and accumulated weight was 66.21 lbs per head. Cow weight gain was 0.93 lbs per day, 11.83 lbs per acre, and accumulated weight was 27.84 lbs per head (table 1). The calf gain per day and total weight gain per head were similar on both treatments, while the calf weight gain per acre was 50.74 lbs (180.7%) greater on the fertilized pasture. The cow weight gain on the fertilized pasture was greater than that on the unfertilized pasture. The cow weight gain on the fertilized pasture was 1.64 lbs per day greater, 23.03 lbs greater total weight per head, and impressively was 80.98 lbs per acre (684.5%) greater (table 1). The dollar value captured was greater on the fertilized pasture, the pasture cost was $9.01 lower, pasture weight gain value was $0.43 greater, net return per cow-calf pair was $8.43 greater, and net return per acre was $28.14 (258.2%) greater (table 2). During the 12 year period of 1983 to 1994, the basal cover of fertilized crested wheatgrass increased (50.0%) from 21.5% to 32.2%, with a decrease to 19.1% during the dry period of 1988 to 1990.

Most of the old crested wheatgrass acreage was abandoned cropland plots that had been plowed rangeland in order to fulfill the compliance requirements of the Homestead Acts of both the United States and Canada. Most of these parcels are located within units that consist of other types of plant cover, like rangeland. These old crested wheatgrass stands developed symbiotic relationships with soil microbes sometime between 25 to 35 years after they were seeded, and if they have been properly managed, those soil microbes should still be active. Fertilization of these old crested wheatgrass areas will greatly decrease the soil microbes. The old crested wheatgrass stands with soil microbes should be managed without fertilizer. The younger crested wheatgrass stands have usually been seeded into wornout cropland without the benefit of copious quantities of barnyard manure applied during the years before seeding. These younger stands of crested wheatgrass may be deficient of essential nutrients. Fertilization of these younger deficient crested wheatgrass pastures can work biologically and economically if 50 lbs N/ac were to be applied one month before the start of grazing, which would be early April. Fertilization applied at later dates results in greatly reduced herbage biomass. It takes a long time period for the fertilizer treatment to effect grass growth. Also the calves need to be on the ground one month before the start of grazing crested wheatgrass; calves less than one month old cannot gain much more than 1.25 lbs/day, which would leave little profit after the fertilizer bill was paid. The older calves make this work economically. Also remember that if the fertilizer treatment is stopped, not many soil microbes remain, and it will take more than 25 to 35 years to regain a soil microbe population.

Fertilizing perennial grasses does not increase herbage production during an entire growing season. Herbage production that would have occurred during one period is moved to overlap the herbage production during an earlier period. Fertilization synchronizes grass tiller development to occur during a short period of time. When crested wheatgrass is fertilized during early April, the increased synchronized tiller growth occurs during May. The vegetative tillers that would have developed during June and July, developed during May and only a few secondary tillers remain to develop a low biomass during that June, with a few fall tillers developing during July and August. The herbage growth from early June to late July was 647.97 lbs (table 3).

During 1995 to 2005, cow and calf weight performance on a crested wheatgrass two pasture switchback stocked at 1.25 ac/AUM (Appendix tables 1-5) was compared to that on an unfertilized pasture stocked at 2.33 ac/AUM (Appendix tables 6-10). On the switchback pastures, calf weight gain was 2.61 lbs per day, 66.60 lbs per acre, and accumulated weight was 76.45 lbs per head. Cow weight gain was 2.60 lbs per day, 65.49 lbs per acre, and accumulated weight was 75.43 lbs per head (table 1). On the unfertilized pasture, calf weight gain was 2.57 lbs per day, 32.93 lbs per acre, and accumulated weight was 72.67 lbs per head. Cow weight gain was 2.05 lbs per day, 26.67 lbs per acre, and accumulated weight was 59.15 lbs per head (table 1). The cow and calf weight gain on the switchback pastures was greater than those on the unfertilized pasture. The calves weight gain was 0.04 lbs per day greater, 3.78 lbs total weight gain per head greater, and 33.67 lbs per acre (102.2%) greater. The cow weight gain was 0.55 lbs per day greater, 16.28 lbs total weight gain per head greater, and 38.82 lbs per acre (145.6%) greater (table 1). The dollar value captured was greater on the switchback pastures, the pasture cost was $9.33 lower, pasture weight gain value was $2.65 greater, net return per cow-calf pair was $11.96 greater, and net return per acre was $23.66 (165.2%) greater (table 2). During the 11 year period of 1995 to 2005, the basal cover of crested wheatgrass on the unfertilized pasture decreased (5.7%) from 21.4% to 20.2%, and the basal cover of crested wheatgrass on the switchback pastures increased (36.6%) from 19.8% to 27.1%.

The cow and calf weight gains per head and per day on the unfertilized pasture were acceptable, however, the weight gains per acre were low for crested wheatgrass standards. Grazing of the one unfertilized pasture for 28 to 30 days during May does not activate the internal grass growth mechanisms. The herbage growth from early June to late July was only 384.83 lbs (table 3).

The cow and calf weight gains per head and per day on the switchback pastures were a little greater than those on the unfertilized pasture, importantly, the cow and calf weight gains per acre were 145.6% and 102.2% greater than those on the unfertilized pasture, respectively. The two pasture switchback spring crested wheatgrass system activated all of the internal grass growth mechanisms yielding greater grass biomass production, greater grass basal cover, and greater development of secondary tillers and fall tillers resulting in greater cow and calf weight gains per head and per day, and remarkably greater weight gains per acre. The herbage growth from early June to late July was 757.62 lbs, with a July peak at 1796.59 lbs (table 3).

Crested wheatgrass meadows are excellent spring complementary pastures during May. Crested wheatgrass is physiologically ready for grazing and the herbage biomass quantity is sufficient for grazing to start in early May. Spring grazing of crested wheatgrass during May synchronizes cattle requirements closely with the herbage production curves and the nutritional quality curves of the grass forage and is an ideal match coordinating grass phenological growth stages with partial defoliation by large grazing graminivores to activate beneficial plant mechanisms and ecological processes. Crested wheatgrass lead tillers contain 19.0% crude protein in early May. A healthy dense stand of crested wheatgrass is capable of producing rapid rates of growth of herbage biomass with most years producing 300 lbs/ac/day while lead tillers are at vegetative growth stages. By mid May, the lead tillers contain 16.2% crude protein when the flower stalks start developing. Some of the advanced lead tillers reach the flower stage by 28 May containing 13.5% crude protein. The rate of growth slows. The crude protein content is at 12.1% during early June. The remaining lead tillers usually reach the flower stage by 10 June. High animal weight gains per head and per day, and incredible weight gains per acre can be achieved without fertilizer by using a two pasture switchback treatment where each of the two pastures are grazed for two alternating periods of 7 to 8 days for a total of 28 to 32 days from early May to late May or to a couple of the first days of June. The calves need to be one month old on 1 May at the start of grazing in order for them to be able to put on high rates of weight gain per day. A minimum of 500 lbs to 1000 lbs of live herbage weight per acre must remain at the end of grazing, more is better. Also, crested wheatgrass pastures should only have one use per growing season.

Crested wheatgrass plants are hardy but cannot fully recover from double heavy use during one growing season. The stand deteriorates with great reductions in basal cover and herbage production. Double use of crested wheatgrass meadows that removes most of the standing dead vegetation has the potential to cause serious mineral deficiencies in the grazing cows blood. Mature lactating cows can develop milk fever or grass tetany while grazing lush spring crested wheatgrass vegetation that contains little standing dead grass. Milk fever is caused by a blood deficiency of calcium (Ca) and grass tetany is caused by a blood deficiency of magnesium (Mg.). Crested wheatgrass live herbage, however, is rarely deficient in calcium or magnesium during the growing season. A cows blood serum deficiency of calcium or magnesium is not caused by consuming crested wheatgrass forage deficient in those minerals. Absorption of most minerals from the forage is by passive transport (diffusion) across the intestinal wall; some calcium is transported with a protein carrier. Only about half of the ingested minerals are absorbed through the intestinal wall into the cows blood system under normal conditions. During the early spring, the rate of forage passage through the cows digestive tract is accelerated when lush vegetation that is high in water and crude protein is consumed without adequate quantities of standing dead vegetation; greatly reducing the quantity of dietary minerals absorbed through the intestinal wall and potentially resulting in deficiencies of calcium or magnesium in the cows blood. Cattle grazing crested wheatgrass pastures containing sufficient amounts of dry standing carryover residual vegetation can maintain normal slow rates of forage passage through the digestive tract and normal rates of mineral diffusion; which in effect, prevents the occurrence of mineral deficiencies in the blood and thus preventing the development of milk fever or grass tetany in cows grazing crested wheatgrass spring (May) complementary pastures.

The grazing start date of spring crested wheatgrass complementary pastures was determined to be 1 May and duration of the grazing period was confirmed to extend to late May or to the first couple of days in June during this study.

In the west river region of the Northern Mixed Grass Prairie, the optimum stocking rate for a one unfertilized spring crested wheatgrass pasture in very good condition was determined to be 2.33 ac/AUM and the optimim stocking rate for a two pasture spring crested wheatgrass switchback system in excellent condition was determined to be 1.30 ac/AUM. During the first few years this treatment was stocked way too heavy at 1.05 ac/AUM, and later 1.25 ac/AUM was tried for several years and found to still be a little too heavy.

During this study, the two pasture switchback grazing treatment was successfully adapted to management of spring (May) grazing on unfertilized crested wheatgrass pastures. This two pasture switchback treatment design is extremely detrimental when used to manage grazing on summer native rangeland pastures because the grazing periods are out of synchronization with the development of grass phenological growth stages. And the reason that it works well for one month (May) on crested wheatgrass pastures is that most of the entire grazing period occurs prior to when the lead tillers reach the flower stage. The first lead tillers to reach the flower stage is usually 28 May with most tillers at flower stage by 10 June. If grazing starts on 1 May and the two alternating grazing periods in each of the two pastures is 7 days long, the end of grazing is 28 May, and if the grazing periods are 8 days long, the end of the grazing is 2 June, while most of the forage material is still vegetative lead tillers.

Grass lead tillers grazed only during vegetative phenological growth stages permits the greater stocking rate compared to native rangeland on the same soil type. However, grazing crested wheatgrass at high stocking rates for 28 to 30 days during May requires the remainder of the growing season for the tillers to fully recover.

Crested wheatgrass meadows do not produce more than native rangeland. The total net primary production of crested wheatgrass herbage biomass during an entire growing season is about the same as that produced on native rangeland. Crested wheatgrass monocultures appear to produce greater herbage than native rangeland because ungrazed crested wheatgrass has one major growth period with most of the lead tillers growing together at a similar time and at a similar rate resulting in a high peak herbage biomass early in the growing season with little new growth occurring after mid to late June. Native rangeland, on the other hand, is a mixture of numerous cool season and warm season species with several growth periods not occurring together but spread throughout the early portion of the growing season resulting in a lower peak herbage biomass extended over a longer period of time, and producing about the same quantity of total new growth material as crested wheatgrass on the same soil type per acre during one growing season.

The ability to start grazing a month ahead of the proper grazing start date on native rangeland is the primary biological advantage of crested wheatgrass pastures and their priority use should be grazing during May as spring complementary pastures in conjunction with summer grazing native rangeland rotation systems starting in early June.

Table 1. Cow and calf weight performance grazing spring crested wheatgrass complementary pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept			Biologically Effective Concept			Biological Gain		
Crested wheatgrass	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs
1989-1994	One Pasture, 2.45 ac/AUM Unfertilized			One Pasture, 0.85 ac/AUM Fertilized 50 lbs N/ac					
Calf	66.21	2.34	28.08	66.83	2.37	78.82	0.62	0.03	50.74
Cow	27.84	0.93	11.83	50.87	2.57	92.81	23.03	1.64	80.98
1995-2005	One Pasture, 2.33 ac/AUM Unfertilized			Two Pasture, 1.25 ac/AUM Switchback					
Calf	72.67	2.57	32.93	76.45	2.61	66.60	3.78	0.04	33.67
Cow	59.15	2.05	26.67	75.43	2.60	65.49	16.28	0.55	38.82

Table 2. Value captured gain in dollars from spring crested wheatgrass complementary pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept				Biologically Effective Concept				Value Captured Gain			
Crested wheatgrass	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $
1989-1994	One Pasture, 2.45 ac/AUM Unfertilized				One Pasture, 0.85 ac/AUM Fertilized 50 lbs N/ac							
Cow-Calf pair	20.65	46.35	25.71	10.90	11.64	46.78	35.14	39.04	-9.01	0.43	8.43	28.14
1995-2005	One Pasture, 2.33 ac/AUM Unfertilized				Two Pasture, 1.25 ac/AUM Switchback							
Cow-Calf pair	19.38	50.87	31.50	14.32	10.05	53.52	43.46	37.98	-9.33	2.65	11.96	23.66

Table 3. Herbage biomass (lbs/ac) recovery following May grazing of crested wheatgrass spring (May) complementary pastures managed with three treatments.

Crested wheatgrass	Apr	May	Jun	Jul	Aug	Sep
1 Pasture, 0.85 ac/AUM Fertilized 50 lbs N/ac						
1983-1994						
Pregrazed	1121.76					
Grazed		518.93	789.62	1166.90	1280.07	718.82
1 Pasture, 2.33 ac/AUM Unfertilized						
1995-2005						
Pregrazed	752.16					
Grazed		797.13	1018.07	1181.96	1101.63	1019.18
2 Pasture, 1.25 ac/AUM Switchback						
1995-2005						
Pregrazed	1330.38					
Grazed		1038.97	1362.88	1796.59	1733.59	1763.57

Summary Native Rangeland Pastures

Native rangeland is the only perennial grass type that can adequately provide nutritious forage to modern lactating cows during the summer period from 1 June to mid October when the ecosystem processes and the internal grass mechanisms are fully activated with partial defoliation by graminivores that removes 25% to 33% of the leaf material from grass lead tillers at phenological growth stages between the three and a half new leaf stage and the flower stage (Manske 1999, 2011).

During 1983 to 1994, cow and calf weight performance grazing three native rangeland pastures with twice-over rotation stocked at 8 cows per 80 acres with 10.22 ac/AU (Appendix tables 11-15) was compared to that on a native rangeland pasture grazed seasonlong stocked at 6 cows per 80 acres during 1983 to 1987 and at 7 cows per 80 acres during 1988 to 1994 with 11.43 ac/AU (Appendix tables 16-20). On the twice-over system, calf weight gain was 317.98 lbs per head, 2.70 lbs per day, and 31.80 lbs per acre, and cow weight gain was 81.58 lbs per head, 0.68 lbs per day, and 8.16 lbs per acre (table 4). On the seasonlong system, calf weight gain was 265.12 lbs per head, 2.35 lbs per day, and 21.99 lbs per acre and cow weight gain was 21.80 lbs per head, 0.19 lbs per day, and 1.67 lbs per acre (table 4). The dry period of 1988 to 1990 resulted in reductions of cow and calf weight performance caused by reduced herbage production with lower nutritional quality and reduced length of the grazing period. On the twice-over system, cow weight gain was reduced 14.89 lbs and calf weight gain was reduced 39.78 lbs. On the seasonlong system, cow weight gain was reduced 6.40 lbs and calf weight gain was reduced 58.35 lbs. The cow and calf weight gain on the twice-over system was greater than those on the seasonlong system. Calf weight gain was 52.86 lbs per head greater, 0.35 lbs per day greater, and 9.81 lbs per acre greater and cow weight gain was 59.78 lbs per head greater, 0.49 lbs per day greater, and 6.49 lbs per acre greater (table 4). The dollar value captured was greater on the twice-over system than those on the seasonlong system. The pasture cost was $16.15 lower, pasture weight gain value was $37.00 greater, net return per cow-calf pair was $53.14 greater, and net return per acre was $6.41 greater (table 5).

The grazing period on the seasonlong system managed with the traditional concept was from mid June to late October. The cows daily weight gain generally lost weight during the first two weeks from mid June to early July with an average loss of 2.19 lbs per day, the cows gained weight at a decreasing rate during 2.5 months from 1 July to 15 September than lost weight for 1.5 months. The seasonlong cows gained weight during 55.6% and lost weight during 44.4% of the 4.5 month grazing period (figures 1 and 2). The seasonlong calf daily gain was below 2.50 lbs per day during the first two weeks when the cows lost weight, the calf weight gain was above 2.50 lbs per day during the 2.5 months that the cows gained weight from 1 July to 15 September and then the calf daily gain dropped below 2.50 lbs per day while the cow lost weight for 1.5 month from mid September to late October (figures 1 and 2).

The grazing period on the twice-over system managed with the biologically effective concept was from early June to mid October. During the first rotation period of 45 days from early June to mid July, the cows daily gain decreased with the vegetation decrease in crude protein, the cow daily gain leveled off when the cows grazed pastures 1 and 2 during the second period, and then halfway through grazing pasture 3 the second period, the cows lost weight. The twice-over cows gained weight during 88.9% and lost weight during 11.1% of the 4.5 month grazing period (figures 1 and 2). During the first five years of this study, the stimulation period was thought to be 60 days long from early June to late July. The cows loss of weight during the last two weeks of the grazing period showed that the stimulation period was actually only 45 days long from early June to mid July. The twice-over calf daily gain was greater than 2.50 lbs per day from 1 June to 30 September and then the calf daily gain dropped below 2.50 lbs per day for the last 2 weeks while the cow lost weight from late September to mid October (figures 1 and 2).

During the 1983 to 1994 period, the cow and calf weight performance on the traditional concept was substantially lower than those for the cow and calf pairs on the biologically effective concept. A great amount of the weight reduction was caused by the differences in the dates of the grazing periods on the traditional concept pastures. The crested wheatgrass pasture was grazed from mid May to mid June and the native pasture was grazed from mid June to late October. The crested wheatgrass pasture was grazed during two weeks in June when the crude protein content was 12% to 10% which had been traded for grazing during two weeks in early May when the crude protein content was 19% to 16%, costing the cows and calves at least 30 lbs. The native rangeland pasture was grazed during the last two weeks in October when the cows lost 26 lbs and the calves gained only 16 lbs which had been traded for grazing during the first two weeks of June when the cows could have gained 30 lbs and the calves could have gained 35 lbs.

During the 1983 to 1994 period, the grazing period on the crested wheatgrass pastures on the biologically effective concept was from mid May to early June with only 20 days of grazing instead of starting during early May with 28 or 30 days of grazing adding 18 lbs or 23 lbs to the calf weight and adding 20 lbs or 26 lbs to the cows weight.

A simple problem of having the wrong dates for the grazing period not coordinated with the grass plant herbage biomass production curves and the nutritional quality curves can cost a great quantity in cow and calf weight performance. The optimum coordinated dates for crested wheatgrass pastures is to graze from 1 May to late May or to the first couple days in June. The optimum coordinated dates for native rangeland pastures is to graze from early June to mid October. These are the grazing period dates used for both the traditional concept and the biologically effective concept pastures during the 1995 to 2005 period.

During 1995 to 2005, cow and calf weight performance grazing three native rangeland pastures with twice-over rotation stocked at 8 cows per 80 acres with 10.34 ac/AU (Appendix tables 11-15) was compared to that on a one native rangeland pasture grazed seasonlong stocked at 7 cows per 80 acres with 11.69 ac/AU (Appendix tables 16-20). On the twice-over system, calf weight gain was 380.47 lbs per head, 2.89 lbs per day, and 37.66 lbs per acre and cow weight gain was 86.92 lbs per head, 0.66 lbs per day, and 8.68 lbs per acre (table 4). On the seasonlong system, calf weight gain was 354.37 lbs per head, 2.65 lbs per day, and 30.61 lbs per acre and cow weight gain was 67.11 lbs per head, 0.50 lbs per day, and 5.91 lbs per acre (table 4). The cow and calf weight gain on the twice-over system was greater than those on the seasonlong system. Calf weight was 26.10 lbs per head greater, 0.24 lbs per day greater, and 7.05 lbs per acre greater and cow weight gain was 19.81 lbs per head greater, 0.16 lbs per day greater, and 2.77 lbs per acre greater (table 4). The dollar value captured was greater on the twice-over system than those on the seasonlong system. The pasture cost was $11.82 lower, pasture weight gain value was $15.16 greater, net return per cow-calf pair was $30.09 greater, and net return per acre was $4.37 greater (table 5).

On the seasonlong system managed with the traditional concept, cow daily gain decreased at an average rate of 47% per month from 1 June to 15 September (figure 3). Lead tillers of native cool season and warm season grasses decrease in crude protein content at an average rate of 24% and 23% per month, respectively, from 1 June to 15 September. The cow daily gain decreased 377% during 15 September to 15 October. The seasonlong cows lost weight the last month of the grazing period during 9 growing seasons (82% of the time). Calf daily gains averaged 2.79 lbs/day from 1 June to 15 September, then daily gains decreased to 2.11 lbs/day during the last month (figure 3). Cow weight accumulation occurred at about 28 lbs/month from 1 June to 15 September, then the cows lost 26 lbs during the last month, which was more than 26% of their accumulated weight. Calf weight accumulation occurred at about 81 lbs/month during the entire grazing period (figure 4).

On the twice-over system managed with the biologically effective concept, cow daily gain decreased at an average rate of 34% during the first month (June), then the rate of daily gain increased each time the cows returned to pastures 1 and 2 for the second grazing period. The small increase in daily gain is assumed to occur for more than 2 weeks when the cows returned to pasture 3 for the second grazing period, however, weight performance data has not been collected during late season interim dates. The cows lost an average of 0.51 lbs/day during the first 2 weeks of October. This loss of cow weight was the result of 4 years (36% of the time) with one month per growing season with severe water deficiency at 22% of LTM during August, September, or October causing an average cow weight loss of 1.93 lbs/day. During the other 7 years (64% of the time) the cow weight gain averaged 0.34 lbs/day during the first 2 weeks of October. Calf daily gain averaged 3.08 lbs/day from 1 June to 15 September, then daily gains decreased to 2.28 lbs/day during the last month (figure 3). Cow weight accumulation occurred at about 32 lbs/month from 1 June to 15 September, then the cows lost 17 lbs, which was about 15% of their accumulated weight. Calf weight accumulation occurred at about 88 lbs/month during the entire grazing period (figure 4).

With both the biologically effective concept and the traditional concept using the same optimum coordinated grazing period dates, the cow and calf weight performance on the traditional concept pastures moved closer to the cow and calf weight performance on the biologically effective concept. However, the twice-over rotation system has a considerable biological and economical advantage over the seasonlong system.

Grazing native rangeland for 4.5 months from 1 June to 15 October (137 days) is the ideal period for the best potential cow and calf weight performance to occur. Grazing before 1 June, when the grass lead tillers have not produced 3.5 new leaves is extremely detrimental for grass herbage biomass production with a reduction between 20% and 45% resulting in secondary problems in lost animal weight gains. Grazing after 15 October when the available quantity of crude protein is deficient, cow and calf weight gains suffer greatly and the removal by grazing of living carryover tillers greatly reduces the following growing seasons grass density and herbage biomass production.

In the west river region of the Northern Mixed Grass Prairie, the optimum stocking rate for one native rangeland pasture in very good condition managed with a seasonlong system is with 7 cows/80 acres at 11.43 ac/AU and 2.60 ac/AUM determined during this study. The optimum stocking rate for three native rangeland pastures in near excellent condition managed with a twice-over rotation system is with 8 cows/80 acres at 10.22 ac/AU and 2.30 ac/AUM determined during this study.

The period of time that the internal grass plant growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency can be activated and the external ecosystem processes carried out by the rhizosphere microorganisms can be enhanced with short chain carbon energy transported from the surpluses in grass tillers to the microbes occurs from 1 June to 15 July with grass lead tillers between the three and a half new leaf stage and the flower stage when grazing graminivores' partial defoliation removes 25% to 33% of the aboveground leaf material and when mineral nitrogen is available in the soil at the 100 lbs/ac threshold level.

Partial defoliation by grazing graminivores is the only method that the grass plant mechanisms and ecosystem processes can be activated. Fire and mowing remove too much of the leaf area and the biomass of wildlife is too low to remove 25% to 33% of the leaf material unless elk or bison can reach the biomass of the domesticated cow herd. This makes domesticated graminivores an indispensable biotic component of functional grassland ecosystems.

The biologically effective twice-over rotation strategy was perfected during this study. This grazing strategy was developed to coordinate partial defoliation events with grass phenological growth stages, meet the nutritional requirements of the grazing graminivores, meet the biological requirements of the grass plants and the rhizosphere organisms, and enhance the ecosystem biogeochemical processes and activate the internal grass plant mechanisms to function at potential levels.

Each of three native rangeland pastures of the twice-over rotation system were grazed two times during the 4.5 month period from early June to mid October. The first grazing period of 15 days occurred between 1 June and 15 July, when grass lead tillers were between the three and a half new leaf stage and the flower stage. The second grazing period of 30 days occurred after 15 July and prior to mid October, when the stimulated vegetative secondary tillers had reached their three and a half new leaf stage. The first pasture grazed each year was the last pasture grazed the previous year. A three year sequence would be ABC, CAB, and BCA.

Table 4. Cow and calf weight performance grazing summer native rangeland pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept			Biologically Effective Concept			Biological Gain		
Native Rangeland	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs
1983-1994	One Pasture, 12.06 ac/AU Seasonlong			Three Pastures, 10.22 ac/AU Twice-over rotation					
Calf	265.12	2.35	21.99	317.98	2.70	31.80	52.86	0.35	9.81
Cow	21.80	0.19	1.67	81.58	0.68	8.16	59.78	0.49	6.49
1995-2005	One Pasture, 11.69 ac/AU Seasonlong			Three Pastures, 10.34 ac/AU Twice-over rotation					
Calf	354.37	2.65	30.61	380.47	2.89	37.66	26.10	0.24	7.05
Cow	67.11	0.50	5.91	86.92	0.66	8.68	19.81	0.16	2.77

Table 5. Value captured gain in dollars from summer native rangeland pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept				Biologically Effective Concept				Value Captured Gain			
Native Rangeland	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $
1983-1994	One Pasture, 12.06 ac/AU Seasonlong				Three Pastures, 10.22 ac/AU Twice-over rotation							
Cow-Calf pair	105.68	185.58	79.91	6.64	89.53	222.58	133.05	13.02	-16.15	37.00	53.14	6.41
1995-2005	One Pasture, 11.69 ac/AU Seasonlong				Three Pastures, 10.34 ac/AU Twice-over rotation							
Cow-Calf pair	102.42	248.06	145.64	12.67	90.60	263.22	175.73	17.04	-11.82	15.16	30.09	4.37

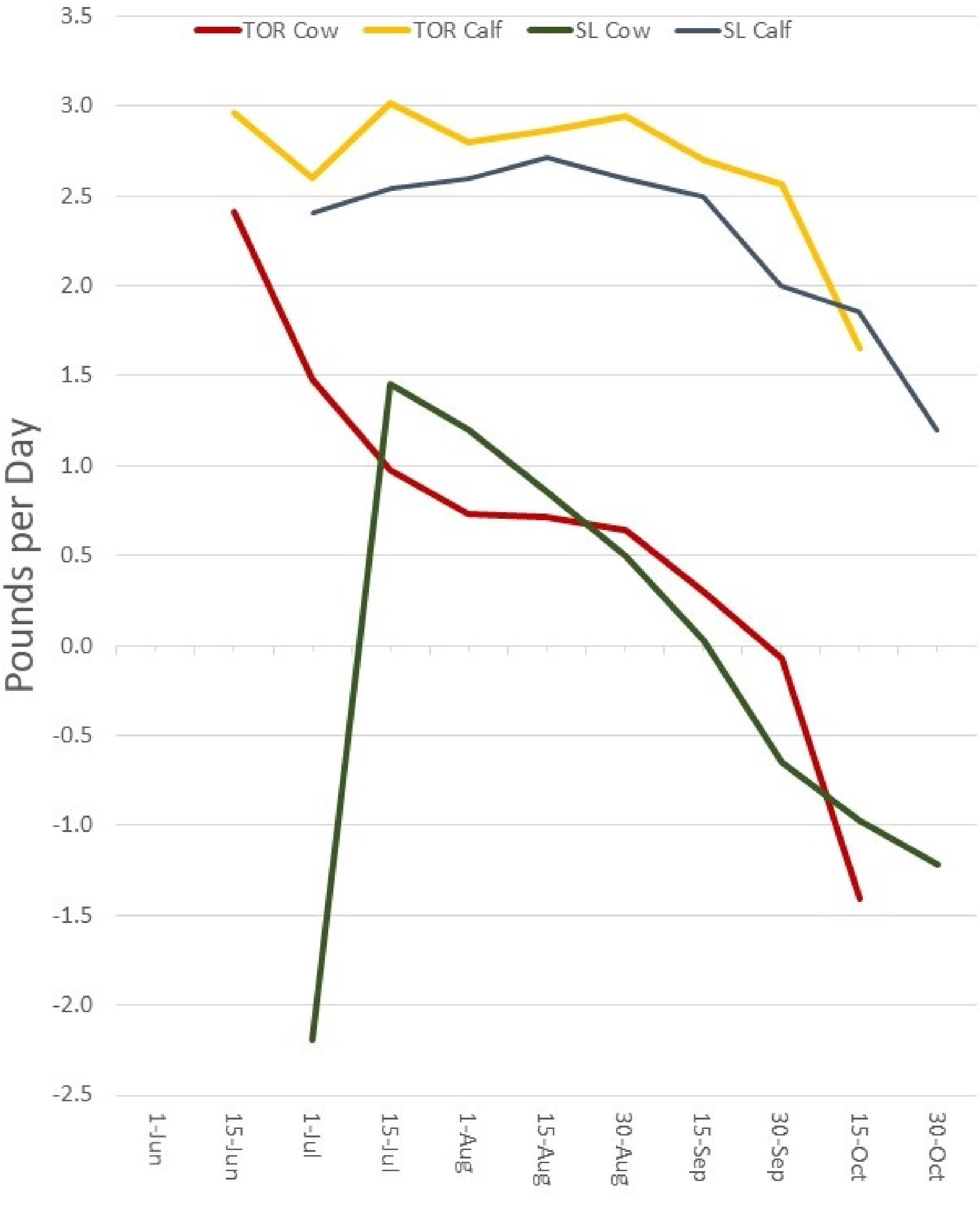

Figure 1. Cow and calf daily gain on the seasonlong and twice-over grazing systems, 1983-1994.

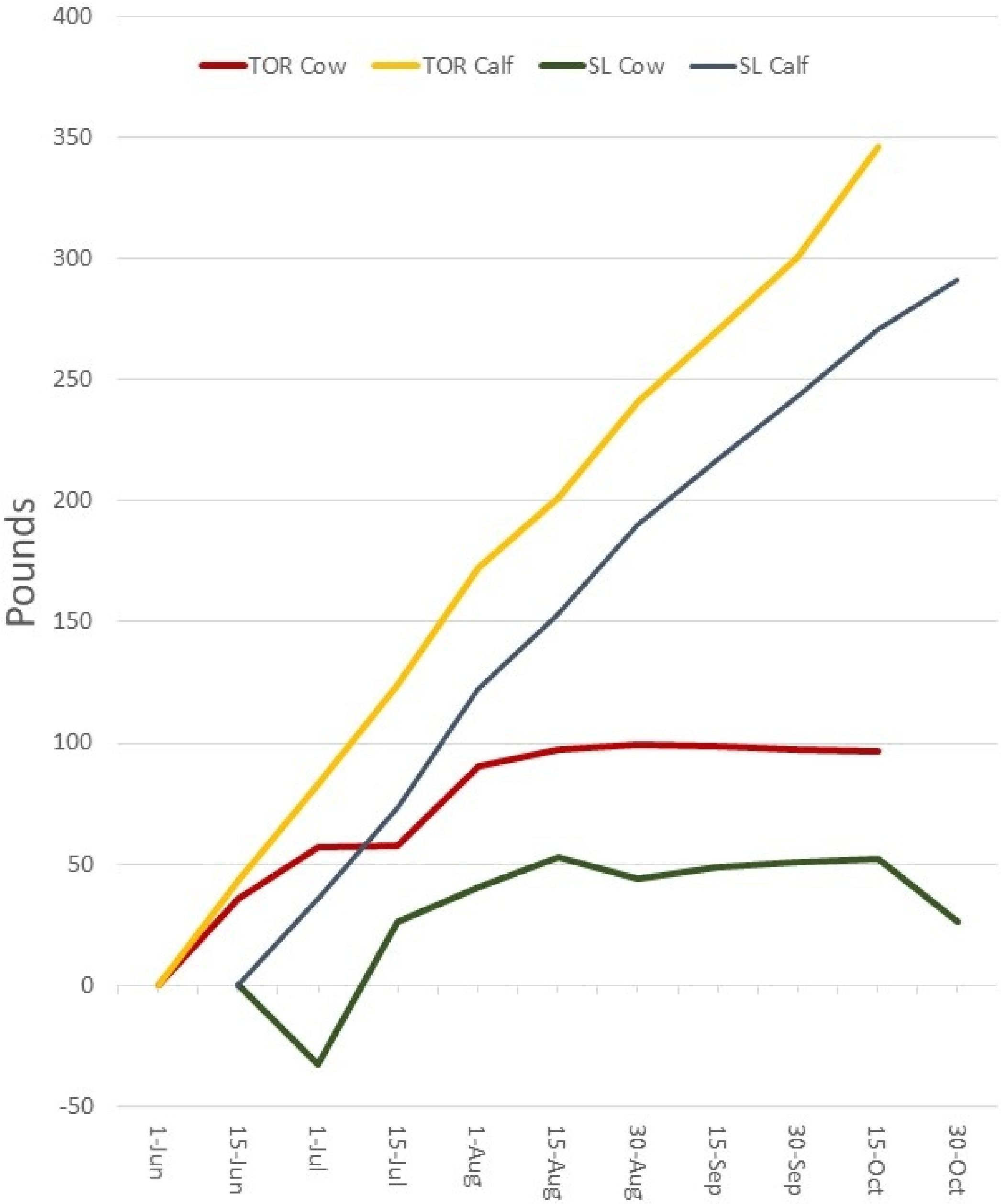

Figure 2. Cow and calf accumulated weight gain on the seasonlong and twice-over grazing systems, 1983-1994.

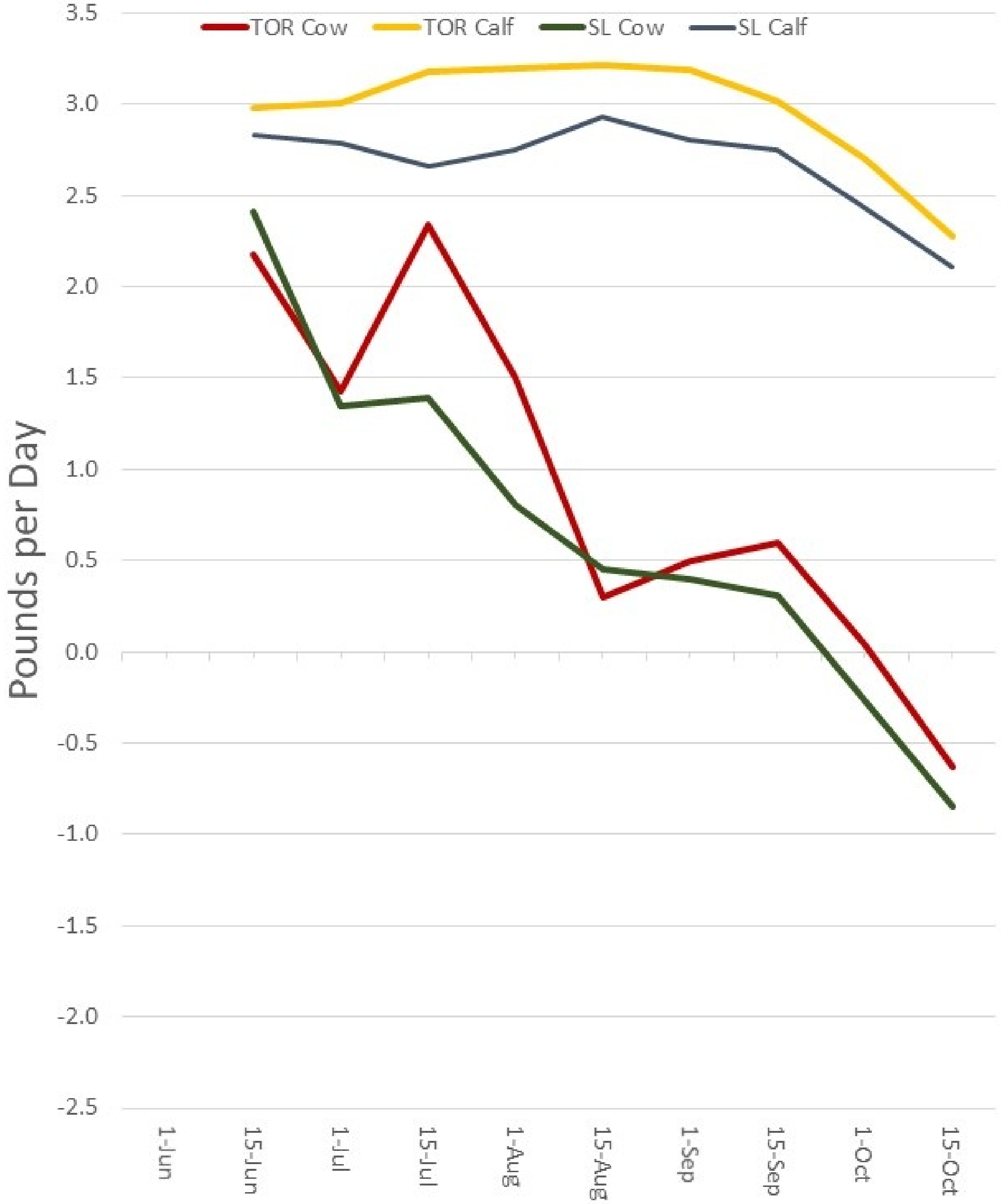

Figure 3. Cow and calf daily gain on the seasonlong and twice-over grazing systems, 1995-2005.

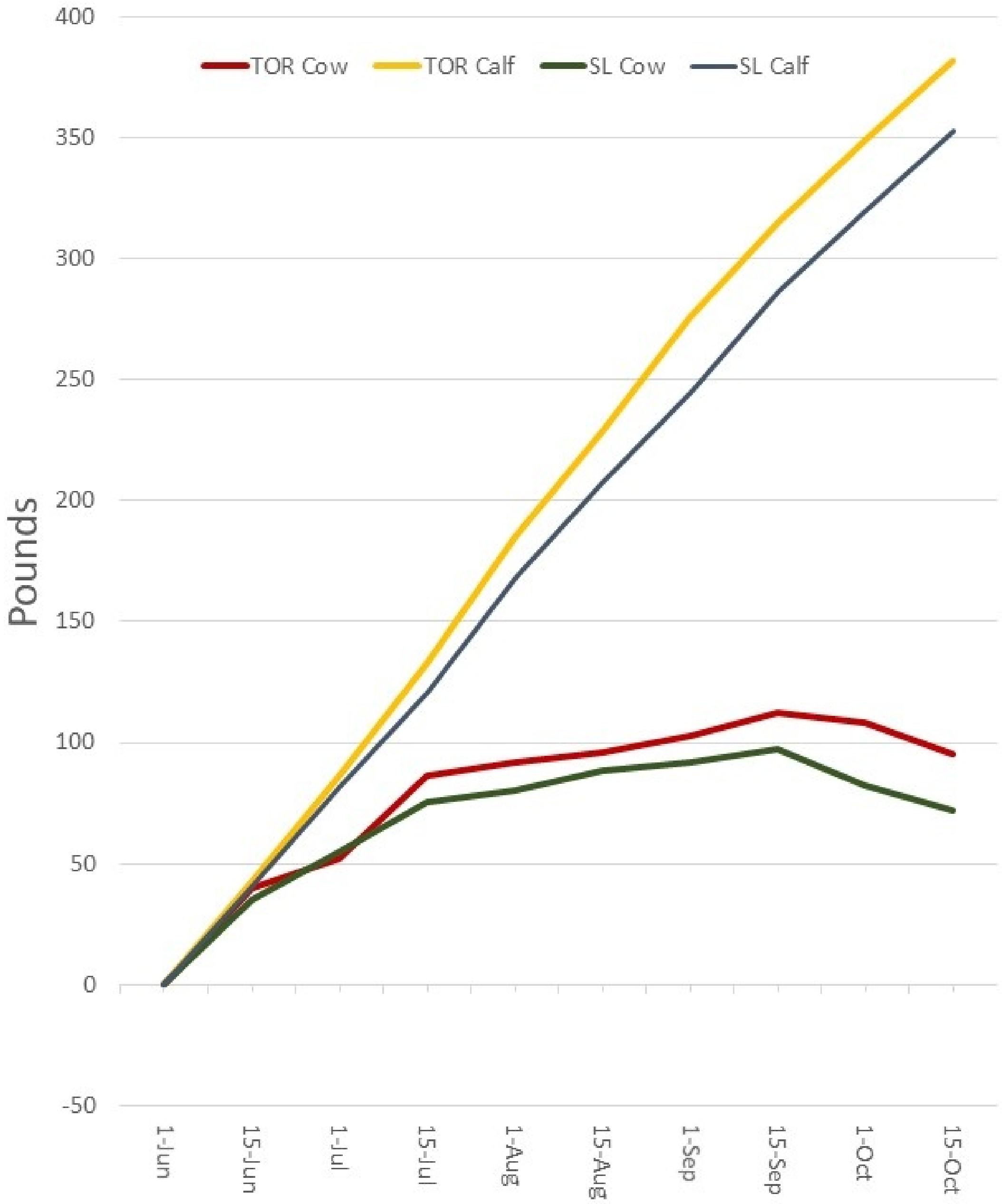

Figure 4. Cow and calf accumulated weight gain on the seasonlong and twice-over grazing systems, 1995-2005.

Fall Complementary Pastures

Native rangeland herbage has low quantity and little quality after mid October. Measured by wet chemistry, late season native rangeland herbage contains around 4.9% crude protein. The Kjeldahl method measures nitrogen content and, during the late season, almost all of this nitrogen is chemically bonded to plant structural components that are not available through rumination. Grazing native rangeland herbage after mid October results in cow average loss of weight at around 0.96 lbs/day and in reductions of calf average weight gain to about 0.91 lbs/day (Manske 2008a). The value of the calf weight gain is usually below pasture costs resulting in negative net returns per cow-calf pair and per acre. Low cash flow costs does not indicate low cost feed. Alternative forage sources that meet livestock dietary quantity and quality are needed during the fall period to capture greater wealth from the land.

Cropland aftermath has been a long-time traditional fall forage type. The nutrient content of stubble from annual cereals harvested for grain is almost nonexistent. Unless the cropland aftermath pasture contains a substantial quantity of sprouted grain, lactating cows cannot find forage that meets their crude protein requirements.

The wildryes are the only perennial grass that retains nutritional quality to meet lactating cows requirements during mid October to mid November. There are numerous species of wildryes in the world. Research at DREC has tested the grazing characteristics of Russian and Altai wildryes. The wildryes have been considered to be difficult to manage because they respond differently than other grasses to standard grassland practices. Which should indicate that the wildryes need to be managed differently than other grasses to be successful.

Annual cereal grasses are typically not used as forage plants for livestock except during emergencies. Winter cereals are usually seeded during summer but this late seeding would not produce sufficient herbage for fall grazing. Spring seeded winter cereals produce sufficient root mass and depth to survive low precipitation periods that can occur during July, August, or September and still produce sufficient herbage for grazing during mid October to mid November. Winter varieties of triticale, wheat, and rye are grown for grain. Triticale produces the greatest herbage biomass but cattle like it the least. Rye produces the lowest herbage biomass and cattle like it the best. Wheat is in the middle. Winter barley does not survive the Northern Plains winters and would not have the problem of leaving plants that need to be sprayed with herbicides or tilled under before the next springs planting. However, because of its winter survival problem, it isn't grown for grain and seed of winter barley is not available locally and long-distance purchases are only sold by the semi load. Because rye is a more dependable crop and has the greater frost and drought resistance, plus cattle like it best, winter (fall) rye was used as the annual cereal forage.

During 1984 to 2002, cow and calf weight performance grazing Altai wildrye pastures stocked at 1.39 ac/AU for 30 days was evaluated (Appendix tables 21-23). During 2003 to 2005, cow and calf weight performance grazing 4 pastures of spring seeded winter cereal stocked at 0.47 ac/AU for 30 days was evaluated (Appendix tables 24-25). During 1983 to 1998, cow and calf weight performance grazing cropland aftermath stocked at 6.63 ac/AU for 30 days was evaluated (Appendix tables 26-27). On the Altai wildrye pastures, calf weight gain was 50.34 lbs per head, 1.82 lbs per day, and 37.12 lbs per acre, and cow weight gain was 42.60 lbs per head, 1.62 lbs per day, and 32.22 lbs per acre (table 6). On the spring seeded winter cereal pastures, calf weight gain was 60.0 lbs per head, 2.00 lbs per day, and 127.66 lbs per acre, and cow weight gain was 31.50 lbs per head, 1.05 lbs per day, and 67.02 lbs per acre (table 6). On the cropland aftermath pastures, calf weight gain was 12.57 lbs per head, 0.42 lbs per day, and 1.90 lbs per acre, and cow weight loss was 48.17 lbs per head, 1.61 lbs per day, and 7.27 lbs per acre (table 6).

The cow and calf weight gain on the Altai wildrye pastures was greater than those on the cropland aftermath pastures. Calf weight gain was 37.77 lbs per head greater, 1.40 lbs per day greater, and 35.22 lbs per acre greater. Cow weight gain was 90.77 lbs per head greater, 3.23 lbs per day greater, and 39.49 lbs per acre greater (table 6). Calf weight gain on the spring seeded winter cereal pastures was greater than those on the Altai wildrye pastures. Calf weight gain was 9.66 lbs per head greater, 0.18 lbs per day greater, and 90.54 lbs per acre greater. The dollar value captured was greater on the Altai wildrye pastures than those on the cropland aftermath pastures. The pasture cost was $1.86 lower, pasture weight gain value was $26.44 greater, net returns per cow-calf pair was $28.30 greater, and net return per acre was $18.98 greater (table 7). The dollar value captured per acre on the spring seeded winter cereal pastures was greater than those on the Altai wildrye pastures. The pasture cost was $8.30 greater, pasture weight gain value was $6.76 greater, net returns per cow-calf pair was $1.54 lower, and net return per acre was $29.14 greater (table 7).

Wildrye pastures deteriorate in 20 to 25 years after they are seeded when managed with standard grassland practices. Previous work on Basin wildrye indicated that the roots extending out past the drip line of wildrye bunch were extremely sensitive to compaction. Observations of driving a pickup or tractor in wildrye pastures killing plants have been made for Altai wildrye, leading to an erroneous conclusion that heavy cows stepping near the crown of wildrye plants were causing plant depletion. Another serious misconception about wildryes is the low herbage biomass production and low quantity of crude protein and total digestible nutrient values collected from ungrazed test plots. Grazing wildryes during the fall period from mid October to mid November changes the growth characteristics of the wildryes.

All perennial grases reproduce vegetatively by producing tillers from axillary buds. These tillers live for two growing seasons, the first year as a vegetative tiller and the second year as a reproductive seed producing tiller. The apical meristem of the major native cool season and warm season grass in the Northern Mixed Grass Prairie change from producing leaf buds to producing flower buds during the second spring when the tiller is between the three new leaf stage and the three and a half new leaf stage; this is one of the reasons grazing readiness occurs after the three and half new leaf stage. Whether or not we have been conscious of the timing of this changeover, our standard grassland management practices are based on this phenomenon. This is also the reason why our standard grassland management practices used on the wildryes causes them to deteriorate. The apical meristem of wildryes, Russian and Altai, change from producing leaf buds to producing flower buds during the second growing season in August, not in the spring like our native grasses. Partial defoliation of wildrye lead tillers during the fall period from mid October to mid November stimulates greater numbers of vegetative tillers to develop from the axillary buds. This greatly increases the herbage biomass production to be over 3000 lbs in mid October at higher quantities of crude protein and TDN permitting cows and calves to gain around 2.0 lbs/day until mid November. The differences in wildrye growth are the reason changes in management are needed. In order to perpetuate a wildrye pasture, no more than 50% of the aboveground herbage can be removed with grazing by mid November, which means about 1500 lbs of herbage must be left standing when the cattle are moved off. If 50% of the aboveground herbage is not left at the end of grazing, the stand deteriorates greatly each year. Using this new insight into the proper management of wildrye pastures, Russian and Altai wildryes should be reconsidered as viable fall perennial grass pastures (Manske 2017a).

Seeding a winter cereal like rye in the spring into fenced cropland with frost free water produces close to 2000 lbs of forage/ac feeding a 1200 lb cow with a calf for 30 days on about 0.5 acres. At low market value for accumulated calf weight of $0.70/lb, the net return per acre is around $48.00. At a market value of $1.25/lb, the net return per acre is around $118.00.

Cropland aftermath of cereal stubble is not a good source of forage for modern livestock, however, with shelter from wind and frost free water, cropland aftermath would be an excellent location to full feed harvested hay to the cow herd during the late season and the barnyard manure would automatically be delivered to the site that it would be beneficial.

Seeding forage barley in the spring into fenced cropland cut for hay at the milk stage produces over 4500 lbs of forage/ac that would feed a 1200 lb cow with a calf for 30 days during the fall from 0.12 acres plus 321 lbs of roughage. At low market value for accumulated calf weight of $0.70/lb, the net return per acre after paying $115.00 for production costs/ac would be around $233.00. At market value of $1.25/lb, the net return per acre is around $498.00 (Manske 2014). Annual cereal grass hay harvested at the proper phenological growth stage has the potential to yield high net returns per acre and should be reconsidered for use as a standard management practice.

Table 6. Cow and calf weight performance grazing fall complementary pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept			Biologically Effective Concept			Biological Gain		
Fall Pasture	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs
1983-1998	One Pasture, 6.63 ac/AU Cropland Aftermath			One Pasture, 1.30 ac/AU Altai wildrye					
Calf	12.57	0.42	1.90	50.34	1.82	37.12	37.77	1.40	35.22
Cow	-48.17	-1.61	-7.27	42.60	1.62	32.22	90.77	3.23	39.49
2003-2005				Four Pasture, 0.47 ac/AU Spring Seeded Winter Cereal					
Calf				60.00	2.00	127.66	9.66	0.18	90.54
Cow				31.50	1.05	67.02	-11.10	-0.57	34.80

Table 7. Value captured gain in dollars from fall complementary pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept				Biologically Effective Concept				Value Captured Gain			
Fall Pastures	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $
1983-1998	One Pasture, 6.63 ac/AU Cropland Aftermath				One Pasture, 1.30 ac/AU Altai wildrye							
Cow-Calf pair	13.26	8.80	-4.46	-0.67	11.40	35.24	23.84	18.31	-1.86	26.44	28.30	18.98
2003-2005					Four Pasture, 0.47 ac/AU Spring Seeded Winter Cereal							
Cow-Calf pair					19.70	42.00	22.30	47.45	8.30	6.76	-1.54	29.14

Total System, Spring, Summer, and Fall Pastures

The total system evaluation of cow and calf weight performance connects to spring, summer, and fall pastures managed by the two distinctly different concepts.

On the Traditional concept system, cow and calf pairs grazed one crested wheatgrass pasture at the rate of 2.33 acres for 28 days during early May to late May, one seasonlong native rangeland pasture at the rate of 11.43 acres for 137 days during early June to mid October, and one cropland aftermath pasture at the rate of 6.63 acres for 30 days during mid October to mid November. The entire system was comprised of 20.39 acres grazed for 195 days (6.39 months) from early May to mid November at a total pasture cost for $133.80 per cow-calf pair, with a cost of $0.69 per day (table 8). Calf weight gain was 439.61 lbs per head, 2.25 lbs per day, and 21.65 lbs per acre (table 9). Cow weight gain was 78.09 lbs per head, 0.40 lbs per day, and 3.83 lbs per acre (table 9). The dollar value captured was $307.73 calf pasture weight gain value, $173.93 net return per cow-calf pair, $8.53 net return per acre, and $0.30 cost per lb of calf weight gain (table 9).

On the Biologically Effective concept system, cow and calf pairs grazed two switchback crested wheatgrass pastures at a rate of 1.30 acres for 28 days during early May to late May, three twice-over rotation native rangeland pastures at a rate of 10.22 acres for 137 days during early June to mid October, and one Altai wildrye pasture at a rate of 1.30 acres for 30 days from mid October to mid November. The entire system was comprised of 12.82 acres grazed for 195 day (6.39 months) from early May to mid November at a total pasture cost of $112.30 per cow-calf pair, with a cost of $0.58 per day (table 8). Calf weight gain was 507.26 lbs per head, 2.60 lbs per day, and 39.57 lbs per acre (table 9). Cow weight gain was 204.95 lbs per head, 1.05 lbs per day, and 15.99 lbs per acre (table 9). The dollar value captured was $355.08 calf pasture weight gain value, $242.78 net return per cow-calf pair, $18.94 net return per acre, and $0.22 cost per lb of calf weight gain (table 9).

The grazing periods occurred at the same time, the number days and the number of months grazed were the same on both concept systems. The Biologically Effective concept system grazed 7.57 fewer acres, at $21.50 lower cost per cow-calf pair, and at $0.11 lower cost per day (table 8). On the Biologically Effective concept system, calf weight gain was 67.65 lbs per head greater, 0.35 lbs per day greater, and 18.01 lbs per acre greater, and cow weight gain was 126.86 lbs per head greater, 0.65 lbs per day greater, and 12.16 lbs per acre greater (table 9). The dollar value captured on the Biologically Effective concept system was $47.35 greater calf pasture weight gain value, $68.85 greater net returns per cow-calf pair, $10.41 greater net return per acre, and $0.08 lower or cost per lb of calf weight gain (table 9).

Using the Traditional concept of management, 400 cow-calf pairs would require 8,156 acres of spring, summer, and fall pastures and would yield $69,572 in net returns for the cow-calf pairs. Using the Biologically Effective concept of management, 400 cow-calf pairs would require 5,128 acres of spring, summer, and fall pastures and would yield $97,112 in net returns for the cow-calf pairs. The 400 cow-calf pairs managed with the Biologically Effective concept would require 3,028 fewer (37.1%) acres and yield $27,540 greater (39.6%) net returns for the cow-calf pairs.

The Traditional concept of management does not consider the biological requirements of the grass plants and soil microbes, and does not consider the crude protein requirements of the cows. As a result, the three biotic components do not produce at their potential levels. When the biotic components of the ecosystem do not function at biological potential, a high percentage of the potential wealth from the land is not captured. In the above example, about 40% of the wealth from the land was not captured.

The Biologically Effective concept of management considers the biological requirements of the grass plants and soil microbes, and provides adequate crude protein from stimulated secondary tillers to meet the cows requirements to late September 100% of the years and to mid October 64% of the years. During the period of May on the crested wheatgrass pastures, the period of early June to mid July on the native rangeland pastures, and the period of mid October to mid November on the Altai wildrye pastures, partial defoliation by the cattle activated the compensatory physiological mechanism, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency internal grass plant growth mechanisms and enhanced the external biogeochemical ecosystem processes performed by the rhizosphere microbes. The activation of all these mechanisms and processes was accomplished by the grazing graminivores with partial defoliation of grass tillers at specific phenological growth stages. When these mechanisms and processes function at biological potentials, the three biotic components of the ecosystem can function at their biological potentials producing greater wealth captured from the properly managed renewable land resources. In the above example, the Biologically Effective concept system captured 140% of the wealth from the land that the Traditional concept system captured.

Table 8. Grazing period, stocking rate, and pasture cost on the Biologically Effective concept system compared to those on the Traditional concept system.

Concept System	Grazing Period	# Days	# Months	Acres per C-C pr	Pasture Cost $	Cost per day $
Traditional	early May-mid Nov	195	6.39	20.39	133.80	0.69
Biologically Effective	early May-mid Nov	195	6.39	12.82	112.30	0.58
Difference	Same	same	same	-7.57	-21.50	-0.11

Table 9. Total cow and calf weight performance and net returns on the Biologically Effective concept system compared to those on the Traditional concept system.

Concept System	Total wt gain lbs	Gain per day lbs	Gain per Acre lbs	Pasture weight gain Value $	Net Return per c-c pr $	Net Return per Acre $	Cost/lb Calf Weight Gain $
Traditional							
Calf	439.61	2.25	21.56	307.73	173.93	8.53	0.30
Cow	78.09	0.40	3.83				
Biologically Effective							
Calf	507.26	2.60	39.57	355.08	242.78	18.94	0.22
Cow	204.95	1.05	15.99				
Difference							
Calf	67.65	0.35	18.01	47.35	68.85	10.41	-0.08
Cow	126.86	0.65	12.16				

Discussion

Grazing graminivores perform two indispensable functions for grassland ecosystems. Graminivores activate the four major internal grass plant growth mechanisms and enhance rhizosphere activity and increase biomass to perform the ecosystem biogeochemical processes, and remove the 50% surplus grass biomass produced by grass plants each growing season.

Grass growth can occur without partial defoliation by graminivores, however, total herbage biomass production is greatly suppressed without the activation of the internal grass growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency. When 100 lbs/ac of mineral nitrogen is available in the soil and all four growth mechanisms are fully activated, grass plants can produce 140% of the removed foliage which would not have been produced without partial defoliation. The activated vegetative reproduction mechanism produce secondary tillers that provide adequate quantities of crude protein for the cows between mid July and late September or mid October. The activated nutrient resource uptake mechanisms increases grass plant competitiveness that prevents weeds, shrubs, and trees from growing in a prairie plant community. The activated water use efficiency permits 50.4% greater grass herbage biomass production per inch of precipitation.

The rhizosphere microorganisms are achlorophyllous and do not have chlorophyll to capture energy and are deficient of energy except when partial defoliation by graminivores causes a transfer of surplus simple carbon energy from grass tillers to the rhizosphere microbes. The resulting greater biomass and activity of the soil microbes mineralize greater quantities of essential elements from the organic form which are unusable by plants into the usable mineral form, primarily nitrogen, which has to be at the threshold level of 100 lbs/ac in order for the grass growth mechanisms to function. The level of available mineral nitrogen in soil managed by the Traditional concept is usually around 50 to 60 lbs/ac which is insufficient to permit the grass growth mechanisms to function. Low soil microbe biomass and activity also prevents the capture of adequate quantities of replacement essential elements which eventually causes ecosystem deterioration.

Grass plants produce double the aboveground herbage biomass than the plants need for photosynthesis for normal growth and maintenance. This extra production has two main purposes: first it ensures the plant can continue proper functions with removal of half the herbage through grazing, and second it attracts grazing graminivores to perform the vital partial defoliation treatments on which the grass plants depend for activation of critical mechanisms. When the double production of herbage biomass is not removed annually by graminivores, it becomes detrimental by shading the young growing leaves the following growing season. In just a couple of growing seasons, the unremoved herbage causes severe reductions in desirable plant species permitting a shift in species composition to less desirable or undesirable plant species, and eventually shrubs then trees can invade the deteriorated prairie plant community as a result of removal of grazing graminivores.

There are no replacement methods that can perform the indispensable functions of grazing graminivores on a fully functional grassland ecosystem.

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Advanced Pasture Forage Management Technology for the Northern Mixed Grass Prairie

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

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component part and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains. The introduction to this study can be found in report DREC 16-1093 (Manske 2016b).

The beef production industry has worked for more than half a century to improve the genetic performance of modern beef animals. As a result, the North American beef herd has been transformed into high-performance, fast-growing meat animals with improved genetic potential and increased nutrient demands. Modern high-performance cattle are larger and heavier, gain weight more rapidly, produce more milk, and deposit less fat on their bodies than the traditional low-performance old-style livestock.

The modern high production range cow has greater nutrient demand that is not simply proportional to the cows greater size. A high performance 1200 lb range cow with average milk production at 20 lb/d, is 20% larger than an old style 1000 lb range cow that had milk production at 12 to 6 lb/d, and requires 27% more energy and 41% more crude protein per day during the lactation production periods than the old style range cow. A high performance 1200 lb range cow with high milk production at 30 lb/d requires 43% more energy and 72% more crude protein per day during the lactation periods than the old style range cow (Manske 2014).

Unfortunately, the forage management technology was not improved simultaneously with beef cow performance. Traditional forage management practices are antagonistic to plant growth mechanisms, suppressive to ecosystem biogeochemical processes performed by the soil microorganisms, inefficient at nutrient capture and conversion, and deficient at providing adequate forage quality during the entire grazing period and harvested forage period for modern livestock at low costs.

Improvements in forage management technology are needed that provide the biological and physiological requirements to the forage grass plants, soil microorganisms, and grazing livestock, that can activate and maintain the grass plant growth mechanisms and the ecosystem biogeochemical processes, that can revitalize soil structure and functionality, that can increase forage quantity and nutritional quality, and that can improve livestock growth and weight performance along with the capture of greater wealth per acre from renewable grassland natural resources.

Grazing forage plants is more efficient and effective when the phenological growth stages, the herbage production curves, and the nutrient quality curves of the forage sources match the biological and physiological requirements of the grazing livestock. This action of coordination between the primary producers and the primary consumers is called "seasonality". All of the perennial forage grasses growing in the region of the Northern Mixed Grass Prairie have growth characteristics that can be categorized into three seasonality units. The spring unit from early May to mid June includes the introduced domesticated cool season grasses, such as crested wheatgrass and smooth bromegrass. The summer unit from early June to mid October includes the cool season and warm season native grasses which can be subdivided into four groups; no domesticated grasses are qualified for the summer unit. The fall unit from mid September to mid November includes all of the wildryes, like Altai and Russian.

A sequence of three separate pastures each consisting of grasses from one of the three seasonality units results in a combined grazing period from early May to mid November with a potential duration of 199 days. The combination of a spring unit pasture of domesticated cool season grass and a fall unit pasture of wildrye grass added to a summer unit pasture of native grass forms a simple three pasture complementary grazing system.

Scientists from two research centers, Swift Current Research Branch in southwestern Saskatchewan and NDSU Dickinson Research Extension Center in western North Dakota, have worked extensively on the development of complementary grazing systems for the Northern Plains. Initially, both research centers used a simple three pasture system with crested wheatgrass, native rangeland, and Russian wildrye, and both research centers have also worked with Altai wildrye as the fall pasture.

In the beginning, practically nothing was known about how to graze crested wheatgrass and Russian wildrye, and the same for Altai wildrye when it was initially studied. Stocking rates, start and stop dates, along with all the other basic information had to be determined through trial and error. The stocking rates for native rangeland were recommended at 70% to 80% removal during the 1920's and 1930's. It wasn’t known until Crider (1955) reported that root growth stoppage varied proportionally with the percentage of aboveground herbage removal and that removal at 50% herbage or greater was detrimental to future productivity. After the dry period in the 1930's, the recommended starting date for native rangeland was mid June. It wasn’t until the early 1980's, that the recommended native rangeland starting date was moved to early June. Grassland ecosystems are complex. It requires a great deal of trial and error research to find the correct answers to simple questions. Research to determine these important answers on how to properly manage complex grassland ecosystems has been conducted at the NDSU Dickinson REC beginning in 1953 continuing through 2018 by Drs. Whitman, Goetz, and Manske.

This report is the synthesis of 66 years of research and will provide the culminated scientific information on the current solutions to the major technological problems that were impeding development of advanced forage management strategies specifically for modern beef livestock on the Northern Mixed Grass Prairie and provide information on the current status of the development of a biologically effective grazing strategy concept with spring and fall domesticated grass pastures complementary to a summer three pasture twice-over rotation system on native rangeland compared to a traditional concept of a simple three pasture complementary grazing system.

Management Treatments

This study evaluates the plant and animal responses to two distinctly different concepts of management of the Spring, Summer, and Fall seasonality pasture units. The Traditional concept managed the grassland resources for their use as forage for livestock. The Biologically Effective concept managed the grassland resources as functional ecosystems and considered the biological requirements of the grass plants, soil microbes, and the livestock.

Spring Complementary Pastures

The traditional spring complementary pasture was crested wheatgrass. Cow and calf pairs grazed one unfertilized pasture of 15 acres (replicated three times) at 2.33 ac/AUM for 28 days (2.14 ac/AU) from early May to early June.

The biologically effective spring complementary pasture was crested wheatgrass. Cow and calf pairs grazed one unfertilized pasture of 26.5 acres split into equal halves with each portion grazed during 2 alternating 7 day periods in a switchback plan (replicated two times) at 1.30 ac/AUM for 28 days (1.20 ac/AU) from early May to early June.

Summer Pastures

The traditional summer rangeland pasture was northern mixed grass prairie. Cow and calf pairs grazed one native rangeland pasture seasonlong (replicated two times) with 7 cows per 80 acres at 2.58 ac/AUM for 135 days (11.43 ac/AU) from early June to mid October.

The biologically effective summer rangeland pastures were northern mixed grass prairie. Cow and calf pairs grazed three native rangeland pastures with a twice-over rotation system (replicated two times) with 8 cows per 80 acres at 2.26 ac/AUM for 135 days (10.22 ac/AU) from early June to mid October.

Fall Complementary Pastures

Four different forage sources for fall complementary pastures have been evaluated that compared two perennial grass forage types and compared two cropland forage types.

The traditional fall complementary perennial grass pasture was native rangeland. Cow and calf pairs grazed one pasture of native rangeland (replicated two times) at 4.11 ac/AUM for 30 days (4.04 ac/AU) from mid October to mid November.

The biologically effective fall complementary perennial grass pasture was Altai wildrye. Cow and calf pairs grazed one pasture of Altai wildrye (replicated two times) at 1.41 ac/AUM for 30 days (1.39 ac/AU) from mid October to mid November.

The traditional fall complementary cropland pasture was cropland aftermath consisting primarily of annual cereal residue of oat and/or barley stubble with some senescent perennial grass on the headlands and waterways. Cow and calf pairs grazed cereal residue forage (replicated two times) at 6.74 ac/AUM for 30 days (6.63 ac/AU) from mid October to mid November.

The biologically effective fall complementary cropland pasture was spring seeded winter cereal. Cow and calf pairs grazed four pastures of spring seeded winter rye with each pasture grazed for one week (replicated two times) at 0.48 ac/AUM for 30 days (0.47 ac/AU) from mid October to mid November.

Commercial crossbred cattle were used on all grazing treatments. Calves were born during March and early April with the average birth date of 16 March and the average birth weight of 95 pounds during the entire study period. The average weight gain between birth and pasture turn out was 95 lbs. Before spring turn out, cow-calf pairs were sorted by cow age and calf age with 50% steers and heifers. At spring turn out, average cow weight was between 1100 lbs and 1200 lbs.

Precipitation

The long-term annual precipitation for DREC ranch in western North Dakota is 17.11 inches (434.56 mm). The perennial plant growing season precipitation (April to October) is 14.47 inches (367.30 mm) and is 84.6% of annual precipitation. The precipitation received in the 3 month period of May, June, and July (8.20 inches) accounts for 47.9% of the annual precipitation. June received the greatest monthly precipitation at 3.19 inches (81.08 mm). Total precipitation received for the 5 month period of November through March averages less than 2.66 inches (15.5% of annual total). Water deficiency conditions occur during 30.6% of the growing season months, this amounts to an average of 2.0 months during every 6.0 month growing season range plants are limited by water stress. Growing seasons with no water deficiency occur during 5.9% of the years. The 3 month periods of May, June, and July experience 31.8% of the water deficient months and August, September, and October experience 64.4% of the water deficient months (table 1) (Manske 2018a).

Procedures

Plant species basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986) with 2000 points collected along transect lines at each replicated vegetation sample site with ungrazed and grazed paired plots.

Aboveground herbage biomass was collected from replicated ungrazed and grazed paired plots by the standard clipping method (Cook and Stubbendieck 1986) with five 0.25 m^2 quadrats (frames) at each sample site. On native rangeland sites, clipping occurred monthly from April through October with herbage material sorted in the field by biotype categories: domesticated grasses, cool season, warm season, upland sedge, forbs, standing dead, and litter. On complementary domesticated grass pastures, clipping occurred monthly from April through November with herbage material sorted in the field by biotype categories: domesticated grasses, other grasses, 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.

Crude protein and phosphorus content were determined for 3 domesticated grasses, 1 upland sedge, 5 cool season grasses, and 4 warm season grasses from samples collected weekly during the growing seasons of 1946 and 1947 at the Dickinson Research Extension Center in western North Dakota. Ungrazed current year's growth of lead tillers was included in the sample; previous year's growth was separated and discarded. Crude protein (N X 6.25) content was determined by the procedure outlined in the Official and Tentative Methods of Analysis (A.O.A.C 1945). Phosphorus content was determined by the method outlined by Bolin and Stamberg (1944). Data were reported as percent of oven dried weight. Plant condition by stage of plant development and growth habit was collected on each sample date. These data are reported as phenological growth stages in the current report. The grass nutritional quality and plant growth stage data were published in Whitman et al. 1951.

Rhizosphere volume was determined from diameter and length measurements by a vernier caliper of western wheatgrass roots contained within two replicated soil cores, 3 inches (7.62 cm) in diameter and 4 inches (10.16 cm) in depth, collected monthly from June to September in silty ecological sites reported as total rhizosphere volume per cubic meter of soil published in Gorder, Manske, and Stroh 2004.

Rhizosphere biomass was determined from fresh rhizosphere material weight which included the rhizosphere organisms, the active plant roots, and the adhered soil particles that had been separated from matrix soil by meticulous excavation with fine hand tools from three replicated soil cores on the silty ecological sites of three replicated grazed pastures managed by the twice-over rotation system collected with a humane soil beastie catcher (Manske and Urban 2012).

Soil mineral nitrogen, nitrate (NO_3) and ammonium (NH_4), was determined for replicated soil core samples collected with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches from silty ecological sites monthly from May to October. Soil samples were frozen soon after 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 using wet chemistry methods.

Percent soil organic matter (SOM) was determined by the loss on ignition (% LOI) analysis conducted by the NDSU Soil Testing Laboratory from replicated soil core samples collected during June at silty ecological sites with the 1 inch Veihmeyer soil tube at incremental depths of 0-6, 6-12, and 12-24 inches.

Individual cows and calves were weighed on and off each treatment pasture, at 15-day intervals during the early portion of the grazing season from early May to mid July, and at 30-day intervals during the latter portion of the grazing season from mid July to mid November. Total accumulated weight gain per head, gain per day, and gain per acre were determined.

Pasture costs were determined using pasture rent values of $8.76 per acre calculated from the mean rent values of the 15 counties in southwestern North Dakota reported for 1993 and 1994 (ND Ag Statistics). Total pasture costs and costs per day were determined. Grazing cropland aftermath cost was determined using rent value of $2.00 per acre.

Market value per pound of calf pasture accumulated live weight gain was determined from the low market value of $0.70 per pound occurring during 1993 and 1994. Net returns per cow-calf pair were determined by subtracting pasture costs from calf pasture weight gain value. Net returns per acre were determined by dividing the net returns per cow-calf pair by the number of acres used per Animal Unit (AU) per seasonality unit.

This study used pasture forage production costs and returns after pasture costs to compare and evaluated biological effectiveness of management concepts during three seasonality pasture periods. This study was not economic analysis of total livestock production costs nor was this a study in livestock marketing schemes.

Table 1. Long-term mean precipitation in inches and % frequency of water deficiency conditions for perennial plant growing season months at DREC Ranch, western North Dakota.

		Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-term Mean Precipitation	inches	1.46	2.65	3.19	2.36	1.96	1.50	1.35	14.47	17.11
% Frequency water deficiency	%	13.9	11.1	11.1	36.1	47.2	52.8	36.1	30.6	

Data from Manske 2018a.

Spring Complementary Pastures

Crested wheatgrass had been introduced into North America during the early portion of the 20th Century and many agricultural scientists had known of the beneficial potential that crested wheatgrass could achieve. However, little practical use had been made of crested wheatgrass before the late 1930's and early 1940's when it was used to revegetate millions of acres of abandoned cropland that had been turned over with steel moldboard plows in order to fulfill the compliance requirements of the Homestead Acts of the United States and Canada. After the end of World War II, the Northern Plains had millions of acres of crested wheatgrass and we did not know how to best graze these grasslands. This need prompted decades of scientific research (Manske 2012).

Crested wheatgrass, *Agropyron cristatum* (L.) Gaertn., is a member of the grass family, Poaceae, tribe, Triticeae, and is a long lived perennial, monocot, cool-season, mid grass, that is highly drought tolerant and winter hardy. Crested wheatgrass was introduced into the United States in 1906 and into Canada in 1915 from Eurasia and was naturalized in the Northern Plains. Numerous accessions of plant material originating from Turkey, Iran, Kazakhstan, central Asia, western and southwestern Siberia, and the steppe region of European Russia have been brought to North America. A total of three recognized species were introduced: Crested wheatgrass, *Agropyron cristatum* (L.) Gaertn., (Fairway type); Desert wheatgrass, *Agropyron desertorum* (Fisch. Ex Link) Schultes, (Nordan type and MT Standard type); and Siberian wheatgrass, *Agropyron fragile* (Roth) Candargy, (Siberian type). Even though each species maintained as isolated plant material has distinct characteristics, specific identification of nonsecluded individual plants is difficult because the morphological variation has developed into a continuum as a result of the extensive intercrossing that has occurred since the 1930's. The separation of this resultant mixture of plants into more than one taxon has proven to be impractical. A taxonomic description of most of this material would be more similar to *Agropyron cristatum*. The first North Dakota record is Stevens 1961. Early aerial growth consists of basal leaves from crown and rhizome tiller buds. Basal leaf blades are 10-20 cm (4-8 in) long, 5-10 mm wide, tapering to a point. Leaves roll inward when dry. The split sheath has overlapping margins that open towards the top. The distinct collar is divided. The membranous ligule is 1-2 mm long with a cut like fringed edge. The small auricles are slender, clasping, and clawlike. The rhizomes are traditionally described as short and the plants are categorized as bunches (caespitose), however, the number and length of the rhizomes and the relative quantities of crown tillers and the rhizomes tillers is determined by the timing of the partial defoliation management and having sufficient quantities of viable green leaf area remaining at end of the treatment. Partial defoliation prior to flowering stimulates the number and length of the rhizomes and increases the quantity of rhizome tillers. Partial defoliation following flowering inhibits rhizome development and decreases the quantity of rhizome tillers. The extensive root system has tough main roots arising from stem crowns and rhizome nodes growing vertically downward producing numerous fine branches forming a dense mass in the top 1 m (3.3 ft) of soil. Several long main roots descend to depths of 2.4 m (8 ft) in loose soil. Regeneration is primarily asexual propagation by crown and rhizome tiller buds. Viable seed production is high and seedlings are vigorous, however, seedlings are successful only when competition from established plants is nonexistent. The numerous flower stalks are erect, slender, 30-80 cm (12-32 in) tall, and hairless. Inflorescence is a flattened dense spike, 5-10 cm (2-4 in) long, that has closely spaced overlapping, laterally compressed spikelets of 3 to 8 florets in two opposite rows with one spikelet per node. Flower period is from late May to mid June. Aerial parts are palatable and nutritious during May. Stocking rates greater than proper for native rangeland can be used during early to late May. Fire top kills aerial parts and kills deeply into the crown when soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reduction in biomass production and tiller density. This summary information on growth development and regeneration of Crested wheatgrass was based on works of Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Zlatnik 1999a, b, Ogle 2006 a, b, Larson and Johnson 2007, Stubbendieck et al. 2011, and Ogle et al. 2013.

Crested wheatgrass starts early leaf greenup in mid April (table 2). The crested wheatgrass tillers have three and a half new leaves around 22 April which is four to five weeks earlier than native cool season grasses. These early new leaves are highly nutritious forage, however, the available herbage weight is insufficient for grazing until 1 May. Early boot stage occurs in mid May and the first stalks with flowers occurs around 28 May (table 2). Most of the lead tillers reach the flower stage during the following 10 to 14 days. The late flowering lead tillers should flower by 10 June. Seed development occurs after the flower stage and seeds reach maturity during the following 5 to 8 weeks (table 2) (Whitman et al. 1951, Manske 1999b).

The nutritional quality of ungrazed lead tillers of crested wheatgrass changes with the tillers' phenological development (table 2). Early season growth stages are high in crude protein and water. The early vegetative leaf stages contain levels of crude protein above 15% during early to mid May. As seed stalks begin to develop in mid May, crude protein levels begin to decrease. At the flower stage, lead tillers contain 13.5% crude protein. The flower stage is when the greatest weight of crude protein per acre occurs. After the flower stage, crude protein levels remain above 9.6% until late June (table 2, figure 1). As the ungrazed lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. By early July, crude protein levels drop below 7.8% and below 6.2% in early August (table 2, figure 1). Phosphorus levels drop below 0.18% in late July (table 2). The patterns of change in nutritional quality are similar from year to year because tiller phenological development is regulated primarily by photoperiod (changes in the length of daylight). Slight variations in nutritional quality result from annual variations in temperature, evaporation, and water stress. Nutritional quality can also be slightly altered by changes in rates of tiller growth and plant senescence. Growth rates are affected by the level of photosynthetic activity, which is affected by air and soil temperature, cloud cover, and availability of hydrogen (from water) for carbohydrate synthesis. Senescence rates increase with high temperatures, precipitation deficiency, and water stress (Whitman et al. 1951, Manske 1999b).

Crested Wheatgrass Management Recommendations

Earlier studies have shown that crested wheatgrass starts growth earlier in the spring than native rangeland and is ready for grazing four weeks earlier than native rangeland. Stocking rates greater than 1.25 ac/AUM are much too heavy. Stocking rates on one pasture strategies can be about 10% heavier than the proper native rangeland stocking rate on the same ecological site. However, grazing periods longer than 32 days on one pasture strategies should use the same stocking rate for native rangeland. Forage utilization greater then 54% and leaving a residual live grass biomass of less than 500 lbs/ac is not enough leaf surface area for plants to fully recover in one growing season causing substantial delays of herbage growth the following spring. Crested wheatgrass plants are hardy but cannot fully recover from double heavy use during one growing season.

Crested wheatgrass alone has adequate crude protein content during the month of May for steers and cow-calf pairs. Grazing studies with 40% to 60% alfalfa showed no clinical signs of bloat in any of the livestock, however, their weight performance was reduced 17%. Weight gains were greater on crested wheatgrass pastures alone than on pastures with alfalfa until the alfalfa was nearly eliminated, then weight gains were the same. Alfalfa has double the water use requirements per pound of dry matter herbage production than grasses. This high water use causes depleted soil water levels to an average of 35% below ambient soil water in a 5 foot radius around each alfalfa plant resulting in water stress conditions and reduced grass herbage production in adjacent grass plants.

Grazing crested wheatgrass pastures for 30 days from mid May to mid June when available crude protein averages 12%, the livestock weight gain is lower than potential. Otherwise, grazing for 30 days from early May to late May when available crude protein averages 17%, the livestock weight gain is much better and close to potential.

Many crested wheatgrass pastures have been seeded into wornout cropland before the organic matter could be replaced with barnyard manure and the soil remains deficient in essential elements. Fertilization of crested wheatgrass pastures can work biologically and economically if 50 lbs N/ac are applied one month (1 April) before the start of grazing (1 May) even if snow remains on the ground; it takes that long of a time period for that treatment to be effective. Fertilization of perennial grasses does not increase total annual production. Fertilization causes tillers of different ages to be synchronized, causing most of the tiller growth to occur together at an earlier but much shorter time span resulting in an apparent greater peak biomass. This also increases the rate of leaf senescence greatly reducing the length of time that the forage has adequate quantities of crude protein. The livestock grazing fertilized pastures have fewer days that the crude protein available meets their requirements than the livestock grazing unfertilized pastures. If cow-calf pairs grazed the fertilized crested wheatgrass pastures, the calves need to be one month old at the start of the grazing period; calves less than one month old cannot gain much more than 1.25 lbs/day. The additional 50 to 60 lbs of weight gain per calf helps pay the fertilizer bill when the annual costs increase. Next time, plan A should be, to increase the organic matter content of the wornout cropland soil before the perennial grass is seeded.

Performance of Grass and Livestock

Crested wheatgrass is an excellent spring (May) complementary pasture. The available herbage biomass provides superior quantity and quality forage from 1 May to the end of May or the first couple of days into June. The crude protein content ranges from 19.0% to 12.1%. Cows with calves one month old on 1 May perform very well while grazing crested wheatgrass; calves less than one month old cannot gain much more than 1.25 lbs/day (Manske 2017b).

The Traditional concept spring strategy used one pasture on unfertilized crested wheatgrass (replicated two times) each with 15 acres grazed for 28 days, stocked at 2.33 ac/AUM (2.14 ac/AU) (table 4).

The Biologically Effective concept spring strategy used a two pasture switchback plan on unfertilized crested wheatgrass (replicated two times) each with 26.5 acres split in half, creating two two pasture switchback systems grazed for 28 days, stocked at 1.30 ac/AUM (1.20 ac/AU) with each half pasture grazed for two periods of 7 days for a total of 14 days on each and 28 days on the 2 halves (table 4). With this simplified version, the pasture switch can always be made during the same day each week i.e. on each Monday morning at 8:00 am. A more complicated version can add four grazing days by making the pasture switch on 8 day periods. Undoubtedly, a system to remind you of the switch days should be developed when using the eight day version.

The one pasture traditional concept provided 1261 lbs/ac herbage during the May grazing period leaving a domesticated grass residual of 797 lbs/ac (table 3, figure 2) which would indicate a utilization rate of 464 lbs/ac. This does not account for a growth rate of about 25 lbs/ac/day. The secondary tiller growth produced 385 lbs/ac between late May and mid July. The basal cover was maintained at a mean of 18.0%.

The two pasture biologically effective concept provided 2183 lbs/ac herbage during the May grazing period, which was 73% greater than that on the one pasture strategy, leaving a domesticated grass residual of 1039 lbs/ac (table 3, figure 2) which would indicate a utilization rate of 1144 lbs/ac. This does not account for a growth rate of greater than 25 lbs/ac/day, with a measured rate of 300 lbs/ac/day during one year between 1 and 28 May. The secondary tiller growth produced 758 lbs/ac between late May and mid July, which was 97% greater than that on the traditional one pasture strategy. The basal cover was maintained at a mean of 22.8% which was 27% greater than the one pasture strategy.

On the switchback strategy, calf weight gain was 2.61 lbs per day, 66.60 lbs per acer, and accumulated weight gain was 76.45 lbs per head. Cow weight gain was 2.60 lbs per day, 65.49 lbs per acer, and accumulated weight gain was 75.43 lbs per head (table 5).

On the one pasture strategy, calf weight gain was 2.57 lbs per day, 32.93 lbs per acer, and accumulated weight gain was 72.67 lbs per head. Cow weight gain was 2.05 per day, 26.67 lbs per acer, and accumulated weight gain was 59.15 lbs per head (table 5).

Cow and calf weight performance on the switchback strategy was greater than those on the one pasture strategy. The calf weight gain per day was 1.6% greater, gain per head was 5.2% greater, and gain per acer was 102.5% greater. The cow weight gain per day was 26.8% greater, gain per head was 27.5% greater, and gain per acre was 145.6% greater (table 5).

Pasture costs were 44.0% lower and cost per day were 43.3% lower on the switchback strategy than those on the one pasture strategy (table 4). The dollar value captured was greater on the switchback strategy, pasture weight gain value was 5.2% greater, net return per cow-calf pair was 33.9% greater, and net return per acre was 138.9% greater, while cost per pound of calf gain was 46.2% lower, than those on the one pasture strategy (table 5).

The two pasture switchback spring crested wheatgrass strategy activated all of the internal grass growth mechanisms yielding greater grass biomass production, greater grass basal cover, and greater development of secondary tillers and fall tillers resulting in greater cow and calf weight gains per head and per day, and remarkably greater weight gains per acre.

Essential Element Absorption

Spring complementary crested wheatgrass pastures should contain a fair amount of standing dead vegetation to slow down the rate of forage passage through the digestive tract of livestock. Management practices that remove most of the standing dead vegetation has the potential to cause serious mineral deficiencies in the grazing cows blood. Mature lactating cows can develop milk fever or grass tentany while grazing lush spring crested wheatgrass vegetation that contains little standing dead grass. Milk fever is caused by a blood deficiency of calcium (Ca) and grass tetany is caused by a blood deficiency of magnesium (Mg). Crested wheatgrass herbage, however, is rarely deficient in calcium or magnesium during the growing season. A cows blood serum deficiency of calcium or magnesium is not caused by consuming crested wheatgrass forage deficient in these minerals. Absorption of most essential minerals is by passive diffusion across the intestinal wall; some calcium is transported by a protein carrier. Only about half of the ingested minerals are absorbed through the intestinal wall into the cows blood system under normal conditions. During the early spring, the rate of forage passage through the cows digestive tract is accelerated when the lush vegetation high in water and crude protein is consumed; greatly reducing the quantity of dietary minerals absorbed through the intestinal wall and potentially resulting in deficiencies of calcium or magnesium in the cows blood. Cattle grazing crested wheatgrass pastures containing sufficient amounts of dry standing carryover residual vegetation can maintain normal slow rates of forage passage through the digestive tract and normal rates of mineral absorption; which in effect, prevents the occurrence of mineral deficiencies in the blood and thus preventing the development of milk fever or grass tetany in cows grazing crested wheatgrass spring (May) complementary pastures.

Summary

Crested wheatgrass meadows are excellent spring complementary pastures during May. Crested wheatgrass is physiologically ready for grazing in early May. The ability to start grazing a month ahead of the proper grazing start date on native rangeland (1 June) and providing adequate quantities of forage with high nutrient content are the primary biological advantages of crested wheatgrass pastures. The optimum use of crested wheatgrass is grazing during May as spring complementary pastures in conjunction with summer grazing native rangeland rotation systems.

Table 2. Agropyron cristatum, Crested wheatgrass, weekly percent crude protein, percent phosphorus, and phenological growth stages of ungrazed lead tillers in western North Dakota, 1946-1947.

Sample Date	Crude Protein %	Phosphorus %	Phenological Growth Satges
Apr 1			
13	15.5	0.256	Early leaf greenup
19	17.1	0.315	
25	16.2	0.313	
May 4	19.0	0.310	Active leaf growth
10	21.0	0.284	
16	16.2	0.255	Flower stalk developing
23	14.5	0.245	
28	13.5	0.247	Flowering (Anthesis)
Jun 6	12.1	0.232	Seed developing
13	11.5	0.255	
19	10.6	0.225	
26	9.7	0.232	
Jul 2	8.6	0.212	Seed maturing
8	7.5	0.191	
16	7.5	0.181	Seed mature
24	6.4	0.178	Drying
30	6.4	0.183	Drying
Aug 6	5.9	0.148	Drying
13	5.8	0.142	
20	5.8	0.151	
26	5.8	0.147	
Sep 3	4.5	0.148	
12	4.0	0.122	
21	-	-	
29	4.7	0.084	
Oct			
Nov 5	4.2	0.090	Drying

Data from Whitman et al. 1951.

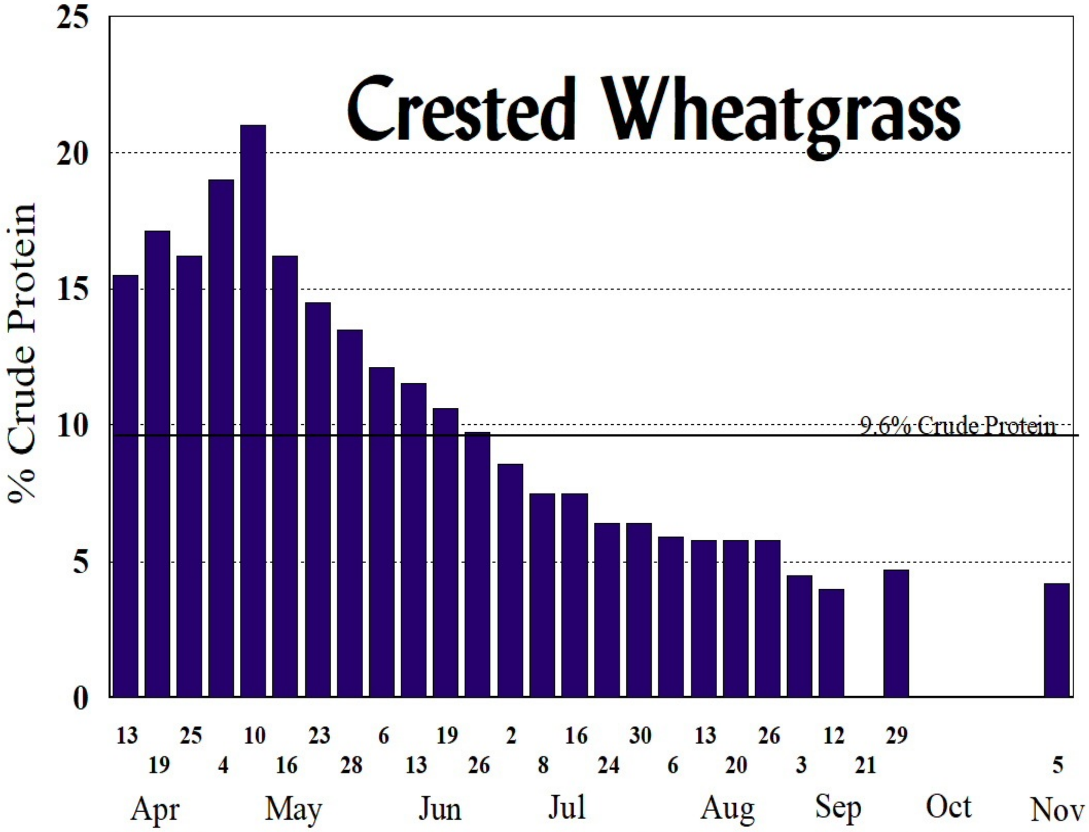

Fig 1. Mean percent crude protein of ungrazed crested wheatgrass in western North Dakota, data from Whitman et al. 1951.

Table 3. Spring herbage biomass (lbs/ac) recovery following May grazing of crested wheatgrass (May) complementary pastures on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Apr	May	Jun	Jul	Aug	Sep
Biologically Effective						
2 Pasture, 1.30 ac/AUM Switchback						
Ungrazed	1330.38	2182.50	2829.06	2570.67	2945.05	2802.96
Grazed		1038.97	1362.88	1796.59	1733.59	1763.57
Traditional						
1 Pasture, 2.33 ac/AUM Unfertilized						
Ungrazed	545.94	1260.70	1265.75	2001.65	1769.43	1992.73
Grazed		797.13	1018.07	1181.96	1101.63	1019.18
% Difference						
Ungrazed	143.7	73.1	123.5	28.4	66.4	40.7
Grazed		30.3	33.9	52.0	57.4	73.0

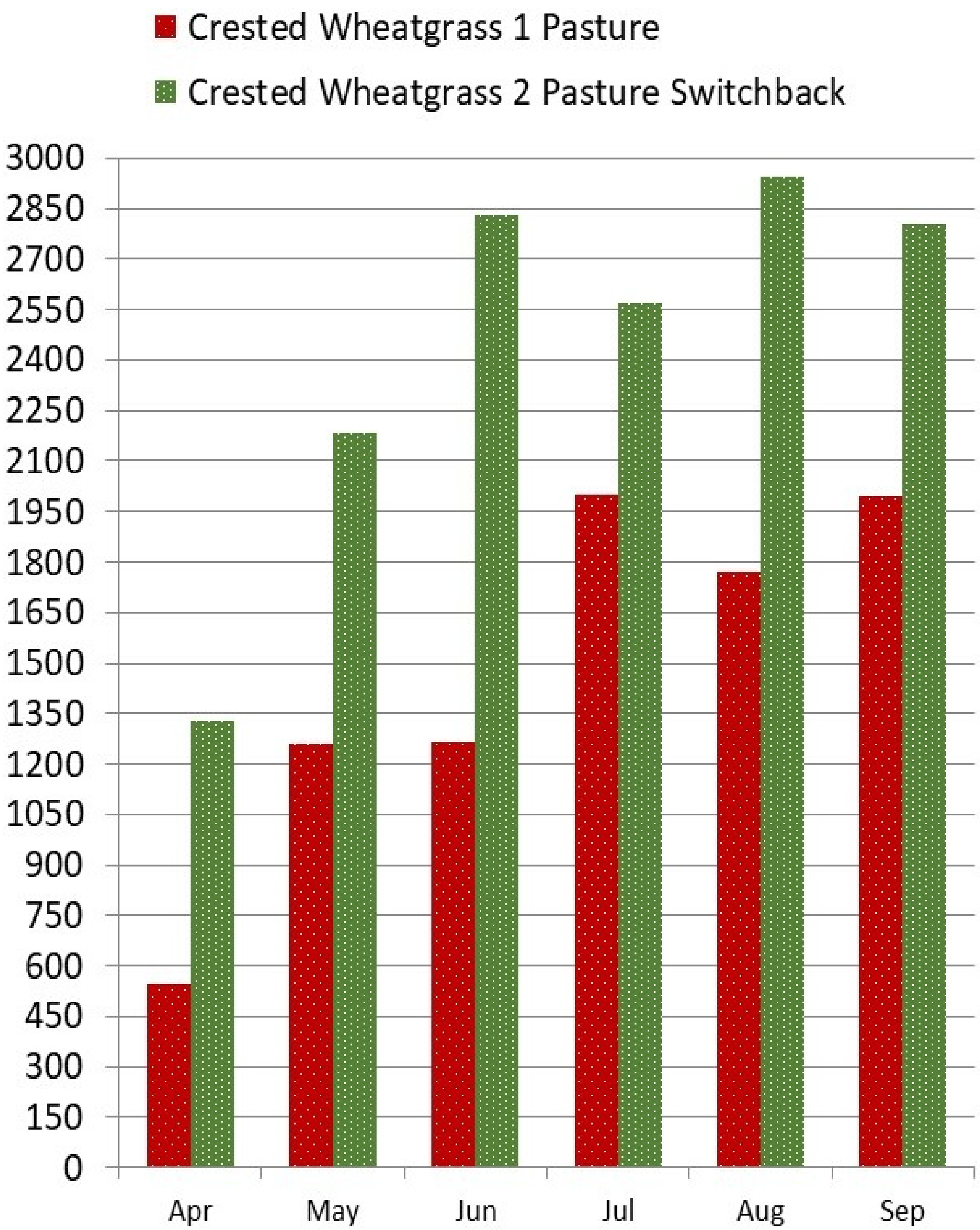

Figure 2. Mean Monthly Crested Wheatgrass Biomass (lbs/ac).

Table 4. Spring grazing period, stocking rate, and pasture cost on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per C-C pr	Acres per AUM	Pasture Cost $	Cost per day $
Biologically Effective	4 May-1 Jun	28	0.92	1.20	1.30	10.51	0.38
Traditional	4 May-1 Jun	28	0.92	2.14	2.33	18.75	0.67
% Difference	same	same	same	-43.93	-44.21	-43.95	-43.28

Table 5. Spring cow and calf weight performance and net returns on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Calf Gain $
Biologically Effective							
Calf	76.45	2.61	66.60	53.52	43.00	35.84	0.14
Cow	75.43	2.60	65.49				
Traditional							
Calf	72.67	2.57	32.93	50.87	32.12	15.00	0.26
Cow	59.15	2.05	26.67				
% Difference							
Calf	5.20	1.56	102.25	5.21	33.87	138.93	-46.15
Cow	27.52	26.83	145.56				

Summer Unit Pastures

The plant species considered to be native to the Northern Plains originated and developed in other regions. At sometime later these plants migrated into the Northern Plains. None of the living plant species growing in the region are known to have originated in the Northern Plains. The plant communities and vegetation types, however, are relatively young and began development in place about 5000 years ago when the current climate with cycles of wet and dry periods began. The diversity of plant species in these young native plant communities permits the vegetation to respond dynamically to changes in climatic conditions by increasing the plant species favored by any set of conditions. This ability to dynamically adjust to changing climatic factors and the capability to provide adequate quantities of nutritious forage during the entire summer period from 1 June to mid October are ideal characteristics for the summer unit pastures. These plant communities are composed of cool season grasses, warm season grasses, and upland sedges with varying composition.

Major Cool Season Grasses

Prairie Junegrass, *Koeleria macrantha* (Ledeb.) Schult, is a member of the grass family, Poaceae, tribe, Poeae, Syn.: *Koeleria pyramidata* (Lam.) Beauv., *Koeleria cristata* (L.) Pers., and is a native, perennial, monocot, cool-season, mid grass, that is cold and heat tolerant, and drought resistant. The first North Dakota record is Bell 1907. Early aerial growth consists of basal leaves arising from crown tiller buds. Prairie Junegrass consistently reaches the 3.5 new leaf stage by 1 June and is an excellent indicator of physiological grazing readiness of native grasses. Basal leaf blades are 8-18 cm (3-7 in) long, 1-3 mm wide, thick, with broad ribs above and a boat prow shaped tip. The split sheath has overlapping translucent margins with short hairs. The indistinctive collar is continuous. The ligule is membranous, 1.5 mm long, often split, continuous with sheath margins, and fringed with hairs. The auricles are absent. The fibrous root system is primarily shallow, with the greatest concentration in the top 3 cm (1.2 in) of soil. The lateral spread is 20-25 cm (8-10 in) outward from the crown. Most main roots are 0.2 mm thick and remain in the top 46 cm (1.5 ft) of soil, with a few main roots descending down to 76 cm (2.5 ft). Regeneration is primarily asexual propagation by crown tillers. Seedling success is low, primarily because of low seed production, and resulting from poor seedling vigor and high mortality. Flower stalks are erect, 30-60 cm (12-24 in) tall. Inflorescence is a narrow, condensed, panicle, 5-15 cm (2-6 in) long, that opens during flowering becoming plume like, then contracting to narrow spike shape after flowering. Spikelets contain 2 florets. Flowers period is early June to mid July. Leaves are highly palatable to livestock. Fire top kills aerial parts and can consume the entire crown when the soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reductions in biomass production and tiller density. This summary information on growth development and regeneration of Prairie Junegrass was based on works of Weaver 1954, Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Simonin 2000, Ogle et al. 2006, Larson and Johnson 2007, and Stubbendieck et al. 2011.

Needle and Thread, *Hesperostipa comata* (Trin. & Rupr.) Barkworth, is a member of the grass family, Poaceae, tribe, Stipeae, Syn.: *Stipa comata* Trin. & Rupr., and is a native, long lived perennial, monocot, cool-season, mid grass, that is highly drought resistant. The first North Dakota record is Bergman 1910. Early aerial growth consists of basal leaves arising from crown tiller buds. Needle and thread consistently reaches the 3.5 (+) new leaf stage by 1 June, however, it rarely retains more than 2 full basal leaves during the early portion of the growing season, eliminating it as an indicator of physiological grazing readiness of native grasses. Basal leaf blades are 10-30 cm (3.9-11.8 in) long, 1-3 mm wide, tapering to a point, with strong ridges on upper surface. Leaves roll inward when dry. The split sheath has overlapping translucent margins. The indistinct collar is continuous and narrow. The ligule is a conspicuous membrane, 3-6 mm long, continuous with sheath margins, often split or frayed. The auricles are absent. This grass is generally considered to be exclusively a bunch grass, however, under proper management, short rhizome tillers can be produced. The extensive fibrous root system is primarily shallow with greater than 50% of the biomass in the top 18 cm (7 in) of soil. The main roots are 1 mm thick and branch profusely with numerous lateral roots. The lateral spread extends 36 cm (14 in) outward from the crown. Several main roots descend down to 91 cm (3 ft) deep with a few main roots extending to 1.8 m (5 ft) deep. Regeneration is primarily asexual propagation by crown tillers. Seedling success is low as a result of poor gemination and competition from established plants. Flower stalks are erect, 30-60 cm(12-24 in) tall. Inflorescence is a narrow panicle with several loosely spreading ascending branches, each with several one flowered spikelets. Flowers are rarely observable because of the prevalence of self fertilization (cleistogamy) within the closed sheath. Floret has a hard sharp pointed base and tip with a 10-

13 cm (4-5 in) long awn that curls as it dries, twisting the seed into the soil. Flower period is late May to late June. The sharp pointed seed with a long awn can cause problems for livestock in hay, however, they rarely cause problems for grazing livestock. Leaves are highly palatable to livestock. Fire top kills aerial parts and fire can consume the entire crown when the soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reductions in biomass and tiller density. This summary information on growth development and regeneration of Needle and thread was based on works of Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Zlatnik 1999c, Ogle et al. 2006, Larson and Johnson 2007, and Stubbendieck et al. 2011.

Western wheatgrass, *Pascopyrum smithii* (Rydb.) A. Love, is a member of the grass family, Poaceae, tribe, Triticeae, syn., *Elymis smithii*, (Rydb.) Gould*, Agropyron smithii* Rydb., and is a native, long-lived perennial, monocot, cool-season, mid grass, that is tolerant of cold, drought, and periodic flooding, has a high tolerance to alkali and saline soils, and moderately shade tolerant. The first North Dakota record is Potter and Greene 1958. Early aerial growth consists of basal leaves arising from rhizome tiller buds. Leaf blades are 5-25 cm (2-10 in) long, 2-4 mm wide, stiff, thick, deeply ridged on the upper surface, tapering to a point. The split sheath has overlapping margins that open toward the top and has a brown or purplish base. The collar is not well defined, continuous, and medium broad. The ligule is a short flat membrane less than 1 mm long. The auricles are long and clasping, sometimes purplish. The creeping rhizome system is extensive. The aggressive rhizomes are primarily in the top 7.6-10.2 cm(3-4 in) of soil. The frequent branches are 15-91 cm (6-36 in) long, produce single or small groups of aerial stems per node at short progressive intervals. The extensive root system has tough, white or light colored main roots 0.5-1.5 mm thick arising from stem crowns and rhizome nodes growing vertically downward regularly producing profuse quantities of short branches that almost completely occupy the soil. Depth of root penetration varies with soil conditions, usually ranging from 1.2 m (4 ft) to 2.1 m (7 ft) deep. Regeneration is primarily asexual propagation by rhizome tiller buds. Seedling success is low as a result of competition from established plants. Flower stalks are erect, hollow, 30-90 cm(11.8-35 in) tall. Inflorescence is an erect compact spike, 3-16 cm (1.2-6.3 in) long, with overlapping solitary spikelets of 3 to 8 florets. Flower period is June. Aerial parts are highly palatable to livestock. Fire consumes aerial parts halting the process of the four major defoliation resistence mechanisms and causing great reductions in biomass production and tiller density. This summary information on growth development and regeneration of Western wheatgrass was based on works of Weaver 1954, Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Trimenstein 1999, Larson and Johnson 2007, Ogle et al. 2009, and Stubbendieck et al. 2011.

Major Warm Season Grasses

Blue grama, *Bouteloua gracilis* (Kunth) Lag. ex Griffiths, is a member of the grass family, Poaceae, tribe, Cynodonteae, and is a native, long lived perennial, monocot, warm-season, short grass, that is drought tolerant, moderately tolerant of alkaline soils, not tolerant of shading and flooding, and intolerant of acidic and saline soils. The first North Dakota record is Bolley 1891. Early aerial growth consists of basal leaves arising from basal tillers lateral to the crown. Basal leaf blades are 3-10 cm (1.2-3.9 in) long, 1-2 mm wide, tapering to a point. The leaves curl when dry at maturity. The split sheath has translucent margins. The collar is continuous and medium broad with long hairs, at the inside sheath edge. The ligule is a dense fringe of hairs 0.5 mm long. The auricles are absent. The short inconspicuous rhizomes facilitate mat formation. The extensive root system is extremely well developed. The main roots are fine, 0.5-1.0 mm thick, taper to 0.2 mm thick, however, having high tensile strength. The great density is attributed to the abundance of branching. The lateral spread is 20-25 cm (8-10 in) outward from the base of the crown. Most roots grow vertically downward to 91 cm (3 ft) deep with a few main roots extending to 1.8 m (6 ft) deep. Fine lateral roots 1.3-2.5 cm (0.5-1.0 in) long, branched to the 3rd order have a frequency of 1.8 per cm (4.3 per in). The greatest root density occurs in the top 46 cm (4.3 in) of soil permitting rapid response to low precipitation events. Regeneration is primarily asexual propagation by lateral basal tillers. Seedling success is low as a result of competition from established plants. Flower stalks are slender, solid pith filled, 16-50 cm (6-20 in) tall. Inflorescence are 2 (rarely 3) eyebrow shaped spikes 2-5 cm (0.8-2.0 in) long with numerous perfect florets clustered all on one side. Flower period is from early July to August. Aerial parts are highly palatable to livestock. Stevens (1963) claimed that blue grama is our most valuable native pasture grass for drier soil. Fire top kills aerial parts and destroys great proportions of the crown material when soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reductions in biomass production and tiller density. This summary information on growth development and regeneration of Blue grama was based on works of Weaver 1954, Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Anderson 2003, Larson and Johnson 2007, Wynia 2007, and Stubbendieck et al. 2011.

Little bluestem, *Schizachyrium scoparium* (Michx.) Nash., is a member of the grass family, Poaceae, tribe, Andropogoneae, syn.: *Andropogon scoparius* Michx., and is a native, long lived perennial, monocot, warm-season, mid grass, that is drought tolerant. The first North Dakota record is Bolley 1891. Early aerial growth consists of basal leaves arising from axillary buds of crown tillers and from fall produced tiller buds on short rhizomes. Leaf blades are usually partially folded along mid rib, 5-15 cm (2-6 in) long, 3-6 mm wide, tapering to a point, bluish green with red tinge, constricted at base. The split sheath has nonoverlapping margins, is strongly keeled, and flattened laterally with purplish base. The collar is continuous and broad. The ligule is a fringed membrane, 0.6-2.3 mm long, with a blunt rounded shape, and covered with short hairs. The auricles are absent. The rhizomes are short and can form mats. The extensive root system has numerous tan roots 0.1-1.0 mm thick, branching profusely to the third and fourth order with many branches 76 cm (30 in) long and diverging at various angles. The lateral spread is 30.5-45.7 cm (12-18 in) outward from base of crown then most roots grow vertically downward to 1.4-1.7 m (4.5-5.5 ft) deep. Finely branched rootlets almost completely occupy the top 76 cm (2.5 ft) of soil. Regeneration is primarily asexual propagation by crown tillers and short rhizome tillers. Seedlings are rare and usually have weak vigor. Flower stalks are erect, fine, wiry, flattened towards base, with solid center of pith, 30-80 cm (12-32 in) tall, red to reddish purple, and not grooved. Inflorescence are numerous, single spicate racemes terminal on stem branches, 2.5-7.6 cm (1-3 in) long. Flower period is from early August to September. Leaves are highly palatable to livestock, however, most animals are reluctant to push their nose into the dense concentration of stiff seed heads. Fire top kills aerial parts and kills deeply into the crown when soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reductions in biomass production and tiller density. This summary information on growth development and regeneration of Little bluestem was based on works of Weaver 1954, Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Steinberg 2002, Larson and Johnson 2007, Stubbendieck et al. 2011, and Tober and Jensen 2013.

Prairie sandreed, *Calamovilfa longifolia* (Hook.) Hack. Ex Scribn. & Southw., is a member of the grass family, Poaceae, tribe, Cynodonteae, and is a native, long lived perennial, monocot, warm-season, tall grass, that is drought resistant, tolerant of alkaline soils, not tolerant of salt and susceptible to trampling. The first North Dakota record is Bergman 1911. Early aerial growth consists of basal leaves arising from fall produced tiller buds, that have very sharp tips located at the terminal ends of rhizome branches. Basal leaf blades are 20-30 cm (8-12 in) long, 4-8 mm wide, coarse, firm, leathery, and tapering to a point. The split sheath has overlapping margins with a pinkish base. The distinct inflated collar is broad and continuous with tufts of long fine hairs on the inner margins. The ligule is a dense ring of hairs 1-3 mm long. The auricles are absent. The extensive rhizomes are more than 30 cm (12 in) long, stout, scaly, have a shiny pale whitish color and are terminal with one tiller. The dense fibrous root system has numerous wiry main roots, 2-3 mm thick, arising from stem crowns and rhizome nodes growing vertically and obliquely downward, mostly in the top 46 cm (18 in) of soil, with lateral branches up to 15 cm (6 in) long developing along the full length of the roots, and has a few long main roots that extend down to 1.5 m (60 in) deep, effectively stabilizing deep sandy soils. Regeneration is primarily asexual propagation by large quantities of rhizome tillers. Seedling vigor is only fair and mortality caused by low soil water in the upper layers is high. Flower stalks are robust, 1-2 m (39-79 in) tall, solitary, forming large colonies. Inflorescence is a panicle 10-40 cm (4-16 in) long with whorled ascending branches, that are semi open. Spikelets are 4-7 mm long, and have one floret with a dense basal ring of white hairs. Flower period is from mid July to September. Seed production is low. The leaves are highly palatable and readily eaten by livestock, however, the coarse stems are not eaten, giving the false impression that this grass is undesirable as forage. Fire top kills aerial parts halting the processes of the four major defoliation resistance mechanisms and causing great reductions in biomass production and tiller density. This summary information on growth development and regeneration of Prairie sandreed was based on works of Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Hauser 2005, Duckwitz and Wynia 2006, Johnson and Larson 2007, and Stubbendieck et al. 2011.

Major Upland Sedges

Threadleaf sedge, *Carex filifolia* Nutt., is a member of the sedge family, Cyperaceae, and is a native, long lived perennial, monocot, cool-season, short graminoid, that is shade tolerant. The first North Dakota record is Bolley 1891. Early aerial growth consists of basal leaves arising from rootstock buds. Basal leaf blades are very fine, thread like, wiry, densely clustered at base with 3 per stem, 7.6-15.2 cm (3-6 in) long, 0.25 mm wide, tapering to a point, usually with edges rolled in, and dark green. Previous years stem and leaf bases are persistent during the following growing season and are chestnut brown. The sheath is papery and squared off at top. The ligule is very a short. The rhizomes are short and black. The extensive fibrous root system has numerous tough, wiry main roots 0.8 mm or less thick, that are resistant to decay as a result of the increased strength from the black pigment, melanin. The lateral spread is from 38 cm (15 in) to 76 cm (30 in) with roots growing obliquely downward, branching profusely, with numerous roots 5 cm (2 in) long. Most main roots descending to 61 cm (24 in) deep and a few long main roots reaching 76 cm (30 in) deep. The terminal ends of the roots are densely appearing broom like (genista). The densest concentration of root mat occurs in the upper 30.5 cm (12 in) of soil. Regeneration is primarily asexual propagation by tiller buds. Flower stalks are erect, triangular in cross section, 10-20 cm (4-8 in) tall. Inflorescence is a solitary terminal narrow spike, 10-25 mm long with male flowers above and a few female flowers below (monoecious). Flower period is from late April to mid June. Aerial parts are highly palatable to livestock. Fire top kills aerial parts and consumes entire crown when soil is dry. This summary information on growth development and regeneration of Threadleaf sedge was based on works of Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, Hauser 2006, and Johnson and Larson 2007.

Needleleaf sedge, *Carex duriuscula* C.A. Mey., is a member of the sedge family, Cyperaceae, syn.: *Carex eleocharis* Bailey, *Carex stenophylla* Wahl., and is a native, long lived perennial, monocot, cool-season, short graminoid, that is drought tolerant. The first North Dakota record is Stevens 1963. Early aerial growth consists of basal leaves arising from rhizome tiller buds. Basal leaf blades are very fine, needle like, stiff, 5-7.6 cm (2-3 in) long, 1-1.5 mm wide, tapering to a point, usually with edges rolled inward. The sheaths are tight and thinning upward. The ligule is wider than long. The dark brown rhizomes are long and slender producing single tillers at 2.5-7.6 cm (1-3 in) progressive intervals. The fibrous root system fans out obliquely downward with numerous main roots that have frequent lateral roots branching to the 2nd and 3rd order forming a dense mat. Regeneration is primarily asexual propagation by rhizome tiller buds. Flower stalks are erect, triangular in cross section, 7.6-20.3 cm (3-8 in) tall. Inflorescence is a solitary, terminal small, spike, 1-2 cm (0.4-0.8 in) long 5-10 mm wide, with male flowers above and few female flowers below (monoecious). Flower period is from May to mid June. Aerial parts are highly palatable to livestock. Fire top kills aerial parts and consumes entire crown when soil is dry. This summary information on growth development and regeneration of Needleleaf sedge was based on works of Stevens 1963, Zaczkowski 1972, Dodds 1979, Great Plains Flora Association 1986, and Johnson and Larson 2007.

Nutrient Quality and Phenological Growth

The available nutritional quality of pregrazed lead tillers of native cool and warm season grasses is closely related to the phenological stages of growth and development, which are triggered primarily by the length of daylight (Roberts 1939, Dahl 1995). The length of daylight increases during the growing season between mid April and 21 June and then decreases. All native cool and warm season grasses have adequate levels of energy throughout the growing season.

Native cool season grasses (table 6, figure 3) start early leaf greenup of vegetative carryover tillers in mid April and grow slowly until early May, reaching 59% of the leaf growth in height by mid May with crude protein levels above 16%. Most cool season grasses reach the 3.5 new leaf stage around early June at 73% of the leaf growth in height, contain levels of crude protein above 15% during early to mid June, reach 94% of the leaf growth in height by late June, and 100% of the leaf growth height by late July. Most cool season grasses reach the flower stage before 21 June. After the flower stage, crude protein levels begin to decrease below 15%. During the seed development stage, flower stalks reach 94% of the growth in height by late June and crude protein levels remain above 9.6% until mid July. The growth in height reaches 100% by late July when seeds are maturing and being shed. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During late July, crude protein levels drop below 8.0% and below 6.5% in late August (Whitman et al. 1951, Goetz 1963, Manske 2000, 2008b). Crude protein levels of cool season secondary tillers increase above 9.6% during July and August to 13.2% in early September, decrease during September, and drop below 9.6% in early to mid October (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late July, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Native warm season grasses (table 7, figure 4) start early leaf greenup of vegetative carryover tillers in mid May, have crude protein levels above 15%, reach 44% of the leaf growth in height by early June, containing crude protein above 13% during early to mid June. Most warm season grasses reach the 3.5 new leaf stage around mid June, reaching 85% of the leaf growth in height by late June and reach 100% of height by late July. Seed stalks begin to develop in mid June and reach the flower stage after 21 June with 12.2% crude protein. During the seed development stage, crude protein levels remain above 9.6% until late July when the flower stalks reach 91% of the growth in height. As the lead tillers mature, the fiber content increases and percent crude protein, water, and digestibility decrease. During mid August, crude protein levels drop below 7.0%, seed stalks reach 100% of the growth in height by late August when the seeds are mature and being shed, and drop below 6.0% in crude protein by early September (Whitman et al. 1951, Goetz 1963, Manske 2000, 2008b). Crude protein levels of warm season secondary tillers increase above 9.0% during August to 10.0% in early September, decreases during September, and drop below 9.6% in late September (Sedivec 1999, Manske 2008b). Phosphorus levels of lead tillers drop below 0.18% in late August, when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

Crude protein levels of upland sedges (table 8, figure 5) do not follow the same relationship with phenological growth stages as in cool and warm season grasses. Crude protein levels in upland sedges remain high through the flower and seed mature stages. Upland sedges grow very early and produce seed heads in late April to early May and crude protein remains above 9.6% until mid July. Crude protein levels decrease with increases in senescence and drop below 7.8% in early August but do not fall below 6.2% for the remainder of the growing season (Whitman et al. 1951, Manske 2008b). Phosphorus levels drop below 0.18% in mid May when plants reach the mature seed stage (Whitman et al. 1951, Manske 2008a).

The quality of grass forage available to grazing graminivores on grasslands of the Northern Plains is above 9.6% crude protein in the lead tillers of the cool and warm season grasses during mid May to late July. Upland sedges have crude protein levels above 9.6% during early May to mid July. The secondary tillers of the cool and warm season grasses have crude protein levels above 9.6% during mid July to late September or mid October.

The early greenup of rangeland grass in the spring is not from new seedlings but from vegetative carryover tillers that did not produce a seedhead during the previous growing season. Spring growth of carryover tillers depends both on carbohydrate reserves and on photosynthetic products from the portions of previous years leaves that overwintered without cell wall rupture and regreened with chlorophyll. Grass tiller growth and development depend, in part, on some carbohydrate reserves in early spring because the amount of photosynthetic product synthesized by the green carryover leaves and the first couple of early growing new leaves is insufficient to meet the total requirements for leaf growth (Coyne et al. 1995). Grass growth also requires that the tiller maintains adequate leaf area with a combination of carryover leaves and new leaves to provide photosynthetic product for growth of sequential new leaves. The total nonstructural carbohydrates of a grass tiller are at low levels following the huge reduction of reserves during the winter respiration period, and the carbohydrate reserves remaining in the roots and crowns are needed for both root growth and initial leaf growth during early spring. The low quantity of reserve carbohydrates are not adequate to supply the entire amount required to support root growth and also support leaf growth causing a reduction in active growth until sufficient leaf area is produced to provide the photosynthetic assimilates required for plant growth and other processes (Coyne et al. 1995). Removal of aboveground leaf material from grass tillers not yet at the three and a half new leaf stage deprives tillers of foliage needed for photosynthesis and increases the demand upon already low levels of carbohydrate reserves.

Performance of Grass, Livestock, and Rhizosphere Microbes

Native rangeland is the optimum summer pasture selection. There are no other perennial forage plant choices that can perform during the full summer period. The lead tillers of native grasses decrease in nutrient content dropping below a lactating cows requirements during the last two weeks of July. Stimulation of vegetative secondary tillers can provide adequate nutrient quality until late September or mid October when the grazing management strategy activates the ecosystem biogeochemical processes and the internal grass growth mechanisms with coordination of partial defoliation by grazing graminivores that removes 25% to 33% of the leaf material from grass lead tillers at phenological growth stages between the three and a half new leaf stage and the flower stage that occurs during the period from 1 June to 15 July each growing season (Manske 1999, 2011).

The traditional concept summer strategy used one native rangeland pasture (replicated two times) managed with a seasonlong system stocked with 7 cows/80 acres at 11.43 ac/AU and 2.58 ac/AUM from 1 June to 14 October (135 days) (table 12).

The biologically effective concept summer strategy used three native rangeland pastures (replicated two times) managed with a twice-over rotation system stocked with 8 cows/80 acres at 10.22 ac/AU and 2.26 ac/AUM from 1 June to 14 October (135 days) (table 12).

The one pasture traditional concept provided 769.96 lbs/ac of mean total cool and warm season grass herbage per month during the entire 4.4 month grazing period. The three pasture biologically effective concept provided 1010.43 lbs/ac of mean total cool and warm season herbage per month during the grazing period which was 31.2% greater herbage per month than provided on the one pasture system (tables 9 and 10).

The biologically effective strategy greatly stimulated secondary vegetative cool and warm season grass tillers. The cool season grass basal cover was 7.02% producing a great lead tiller herbage peak of 760.51 lbs/ac in July and producing a greater secondary vegetative tiller herbage peak of 826.89 lbs/ac in September. The warm season grass basal cover was 15.95% providing a lead tiller herbage peak of 333.21 lbs/ac in August with secondary vegetative tillers producing herbage biomass greater than 300 lbs/ac during September and October (tables 9 and 11, figure 6).

The traditional strategy stimulated low amounts of secondary vegetative cool and warm season grass tillers. The cool season grass basal cover was 5.85% producing a lead tiller herbage peak of 606.10 lbs/ac in July and producing a small increase in herbage biomass of 33.31 lbs/ac attributed to secondary vegetative tiller growth in September. The warm season grass basal cover was 8.76% providing a lead tiller herbage peak of 287.08 lbs/ac in August with an average decrease of 54.90 lbs/ac in herbage biomass during September and October (tables 10 and 11, figure 7).

The stimulated vegetative cool season grass tillers on the biologically effective strategy had a basal cover that was 20.0% greater, produced a herbage peak biomass in July that was 25.5% greater, and produced a herbage peak biomass in September that was 50.7% greater than those on the traditional strategy. The stimulated vegetative warm season grass tillers on the biologically effective strategy had a basal cover that was 82.1% greater, produced a herbage peak biomass in August that was 16.1% greater, and produced herbage biomass during September and October that was 29.9% greater than those on the traditional strategy.

The mean upland sedge herbage production was 14.2% greater and the mean forb herbage production was 40.0% greater on the traditional concept than those on the biologically effective concept (tables 9 and 10). The increased cool and warm season grass density and herbage production on the twice-over strategy suppressed the upland sedge and forb production.

Native rangeland pastures managed with traditional concepts consistently experience deficiencies in herbage quantity and nutrient quality after mid to late July when the lead tillers are producing seeds. Native rangeland pastures managed with biologically effective concepts consistently experience stimulated secondary vegetative tiller growth that provides additional live grass herbage containing adequate quantities of nutrients to meet the requirements of lactating cows from late July to late September or mid October. The stimulated vegetative tiller growth provides the additional nutrients that improve cow and calf weight performance.

On the biologically effective twice-over rotation strategy, calf weight gain was 2.89 lbs per day, 37.66 lbs per acre, and accumulated weight gain was 380.47 lbs per head. Cow weight gain was 0.66 lbs per day, 8.68 lbs per acre, and accumulated weight gain was 86.92 per head (table 13, figures 8 and 9).

On the traditional seasonlong strategy, calf weight gain was 2.65 lbs per day, 30.61 lbs per acre, and accumulated weight gain was 354.37 lbs per head. Cow weight gain was 0.50 lbs per day, 5.91 lbs per acre, and accumulated weight gain was 67.11 per head (table 13, figures 8 and 9).

Cow and calf weight performance on the biologically effective twice-over rotation strategy was greater than those on the traditional seasonlong strategy. Calf weight was 7.4% greater per head, 9.1% greater per day, and 23.0% greater per acre and cow weight gain was 29.5% greater per head, 32.0% greater per day, and 46.6% greater per acre than those on the traditional strategy (table 13).

Dollar value captured was greater on the biologically effective strategy than those on the traditional strategy. Pasture cost was 10.6% lower and cost per day was 10.8% lower on the biologically effective strategy (table 12). Pasture weight gain value was 7.4% greater, net return per cow-calf pair was 19.5% greater, and net return per acre was 33.7% greater, while cost per pound of calf weight gain was 14.3% lower on the biologically effective strategy (table 13).

Properly functioning grassland ecosystems depend on a large active biomass of rhizosphere microbes. The primary management goal is to increase the rhizosphere microbe biomass to a high level and then to maintain that large biomass each growing season. The fungi, bacteria, and protozoa in the rhizosphere do not have chlorophyll nor direct access to sunlight and, consequently, these microbes are deficient of energy and require an outside source of simple carbon energy. Contrary to common assumptions, there isn't enough short chain carbon energy in recently dead plant material and there isn't enough energy in natural plant leakage to support a large active biomass of soil microbes. The only readily accessible source of large quantities of short chain carbon energy is the surplus fixed carbon energy photosynthesized by grass lead tillers at vegetative phenological growth stages. Grass plants fix a great deal more carbon energy than they use, furthermore, grass plants do not store this surplus fixed energy until the winter hardening period, which starts in mid August. Surplus carbon energy is usually broken down during night respiration. However, grass lead tillers at vegetative growth stages can be manipulated to exudate the surplus carbon energy into the rhizosphere through the roots following removal of 25% to 33% of the aboveground leaf biomass by grazing graminivores. This technique supplies sufficient quantities of short chain carbon energy into the rhizosphere initiating the production of large increases in microbe biomass and activity when 60% to 80% of the lead tiller population are partially defoliated by grazing graminivores during the 45 day stimulation period from 1 June to 15 July.

A rhizosphere volume study with replicated soil cores collected monthly evaluated the effects from three management strategies during study year 20. The management strategies were nongrazed, seasonlong, and twice-over rotation. The third pasture of the twice-over system was grazed during the first grazing period from 1 to 15 July. At that time, surplus carbon energy was exudated from partially defoliated lead tillers through the roots and into the rhizosphere. The rhizosphere microbe biomass increased and the biogeochemical processes that mineralize organic nitrogen into mineral nitrogen greatly increased. By the mid August sample period, the rhizosphere volume had increased 85.7% from the July volume (table 14, figure 10).

Initiation of a twice-over strategy on native rangeland that had previously been managed by nongrazing or traditional seasonlong practices will have a rhizosphere microbe biomass that is low or very low and it will require about three growing seasons to increase the microbe biomass large enough to mineralize 100 lbs/ac of mineral nitrogen. The response from the rhizosphere microbes is not instantaneous. During the first two growing seasons, the increase in rhizosphere biomass is less than 24% change. During the third growing season, the biomass could increase 74%. With the available data, the biomass of mineralized organic nitrogen into mineral nitrogen cannot be determined from the biomass of the rhizosphere, because the relationship between microbe biomass and available mineral nitrogen is not linear. The threshold quantity of mineral nitrogen at 112 kg/ha (100 lbs/ac) must be available in order to fully activate the internal grass growth mechanisms of water use efficiency, vegetative reproduction by tillering, and compensatory physiological processes. The largest rhizosphere biomass measured during this study has been 406 kg/m^3 which apparently mineralized 176 kg/ha (157 lbs/ac) of mineral nitrogen. The quantity of 111 kg/ha (99 lbs/ac) of mineral nitrogen was apparently mineralized by a rhizosphere biomass of 214 kg/m^3 (table 15). In order to provide mineral nitrogen at 112 kg/ha (100 lbs/ac) or greater, the management strategy must maintain a rhizosphere biomass somewhere between 214 kg/m^3 and 406 kg/m^3. The twice-over rotation system is the only management strategy known to be able to maintain a large biomass of rhizosphere microbes.

Native Rangeland Management Recommendations

At the start of this study, the consensus of the experienced range scientists of the Northern Mixed Grass Prairie had concluded that the grazing start date of native rangeland was 15 June based on percent reduction of potential herbage biomass determined by the research of Campbell (1952) and Rogler et al. (1962). Data collected during the early portion of this study showed that native rangeland grass were able to survive and thrive from partial defoliation of 25% to 33% after the 3.5 new leaf stage. This phenological growth stage occurred during early June for most cool season grasses and during mid June for the warm season grasses. This new information changed the recommended grazing start date to 1 June for rotation grazing systems and, ten years later, the grazing start date for seasonlong pastures was moved to 1 June.

Moving the grazing start data of seasonlong management strategies from 15 June to 1 June resulted in an increased cow weight gain per head of 207.8%, gain per day of 163.2%, and gain per acre of 253.9%, and an increased calf weight gain per head of 33.7%, gain per day of 12.8%, and gain per acre of 39.2%; the calf pasture weight gain value increased 33.7%, net return per cow-calf pair increased 85.1%, and net return per acre increased 94.9%.

Moving the grazing start date from 15 June to 1 June and implementing a twice-over rotation management strategy resulted in an increased cow weight gain per head of 298.7%, gain per day of 247.4%, and gain per acre of 419.8%, and increased calf weight gain per head of 43.7%, gain per day of 23.0%, and gain per acre of 71.3%; the calf pasture weight gain value increased 43.5%, net return per cow-calf pair increased 121.3%, and net return per acre increased 160.5%.

The increase in cow and calf weight gain of the seasonlong strategy resulted from trading two weeks of grazing herbage during late October at 5.0% crude protein for two weeks of grazing herbage during early June at 14.3% crude protein. The increased nutrient quality of the herbage during early June also increased cow and calf weight gain on the twice-over rotation strategy. The additional weight gain for cows and calves on the twice-over strategy resulted from the increased herbage biomass and improved nutritional quality provided by the stimulated vegetative secondary tillers during late July to late September or mid October.

Moving the grazing start data to 1 June, add a critical 14 days to the period of time that vegetative secondary tillers can be stimulated for a total period of 45 days from 1 June to 15 July each year.

Crested wheatgrass lead tillers decrease in crude protein content as they develop through the phenological growth stages with the rate of decline increasing after the flower stage on 28 May, by 1 June the crude protein content is at 12.8%. The crude protein content of native rangeland grasses on 1 June is at 15.3% which is 20% greater. This becomes the time (1 June) to move off crested wheatgrass spring pastures unto native rangeland pastures.

The management of grazing livestock on grasslands is much more than just providing grazeable forage to feed growing animals. Grassland renewable natural resources are functioning ecosystems. Grassland ecosystems are operative because of multitudes of biogeochemical processes performed by numerous trophic levels of soil microorganisms. Without the soil microbes, grassland resources would no longer be renewable. These indispensable soil microbes living in the rhizosphere surrounding active perennial grass roots require specific consideration in management practices. In addition, grass plants have numerous internal growth mechanisms that permit grasses to produce herbage and to respond to partial defoliation by replacing removed leaf and stem biomass. This study has determined that four of the grass growth mechanisms are important enough to require specific consideration in management practices.

The basic science of the critical internal grass plant growth mechanisms, the rhizosphere microorganisms, and the major ecosystem biogeochemical processes have been described by physiologists, unfortunately, these descriptions failed to provide instruction on how to apply this critical information to the stewardship of intact grassland ecosystems. The management procedures on how to activate these mechanisms and processes were developed during this study.

The 45 day time period of 1 June to 15 July was determined to be the only period when the internal grass plant growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency could be activated. A threshold of 100 lbs/ac of mineral nitrogen had been previously determined to be necessary to fully activate the water use efficiency mechanisms and the same threshold of a minimum of 100 lbs/ac of mineral nitrogen was determined during this study to also be necessary to fully activate the vegetative reproduction by tillering and the compensatory physiological mechanisms. This same 45 day period was also determined during this study to be the only period when the ecosystem biogeochemical processes performed by the rhizosphere microorganisms could be enhanced by moving surplus short chain carbon energy from grass lead tillers through the roots into the rhizosphere to provide energy to the microbes. This outside source of short chain energy is absolutely necessary to increase the microorganism biomass and activity. During this 45 day time period, native grass lead tillers are at phenological growth stages between the three and a half new leaf stage and the flower stage. At these growth stages, partial defoliation from grazing graminivores that removes 25% to 33% of the aboveground leaf material from 60% to 80% of the lead tillers activates all of these beneficial mechanisms and processes, which are required for grassland ecosystems to function properly at their biological potential.

Management of the Twice-over System

The biologically effective twice-over rotation strategy was designed to coordinate partial defoliation events with grass phenological growth stages, to meet the nutrient requirements of the grazing graminivores, the biological requirements of the grass plants and the rhizosphere microorganisms, to enhance the ecosystem biogeochemical processes, and to activate the internal grass plant growth mechanisms in order for grassland ecosystems to function at the greatest achievable levels.

The twice-over rotation grazing management strategy uses three to six native grassland pastures. Each pasture is grazed for two periods per growing season. The number of grazing periods is determined by the number of sets of tillers: one set of lead tillers and one set of vegetative secondary tillers per growing season. The first grazing period is 45 days long, ideally, from 1 June to 15 July, with each pasture grazed for 7 to 17 days (never less or more). The number of days of the first grazing period on each pasture is the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture to the complete system. The forage is measured as animal unit months (AUM's). The average grazing season month is 30.5 days long (Manske 2012). The number of days grazed are not counted by calendar dates but by the number of 24-hr periods grazed from the date and time the livestock are turned out to pasture. The second grazing period is 90 days long, ideally from 15 July to 14 October, each pasture is grazed for twice the number of days as in the first period. The length of the total grazing period is best at 135 days; 45 days during the first period plus 90 days during the second period. There is some flexibility in the grazing period dates. The starting date has a variance of plus or minus 3 days with a range of start dates from 29 May to 4 June. This gives an extreme early option to start on 29 May with the first period to 12 July and with the second period to 11 October. The extreme late alternative option can start on 4 June with the first period to 18 July and with the second period to 17 October. There is also the option to add a total of 2 days to the total length of the grazing period. These 2 days can be used when a scheduled rotation date occurs on an inconvenient date by adding one day to each of two rotation dates. The limit of additional days is two per year resulting in a total length of 137 days. If inconvenient rotation dates occur during 3 or more times, an equal number of days greater than two must be subtracted from the grazing season, so total number of days grazed per year does not exceed 137 days. If the start date is later than 4 June, the scheduled rotation dates must remain as if the start date were on 4 June, in order to maintain the coordinated match of the partial defoliation events with the grass phenological growth stages. The total number of days grazed will be 135 days minus the number of days from 4 June to the actual start date. However, it is best to start on 1 June each year.

During the first period, partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers between the 3.5 new leaf stage and the flower stage increases the rhizosphere microbe biomass and activity, enhances the ecosystem biogeochemical processes, and activates the internal grass plant growth mechanisms. Manipulation of these processes and mechanisms does not occur at any other time during a growing season. During the second grazing period, the lead tillers are maturing and declining in nutritional quality and defoliation by grazing is only moderately beneficial to grass development. Adequate forage nutritional quality during the second period depends on the activation of sufficient quantities of vegetative secondary tillers from axillary buds during the first period. Livestock are removed from intact grassland pastures in mid October, towards the end of the perennial grass growing season, in order to allow the carryover tillers to store the carbohydrates and nutrients which will maintain plant mechanisms over the winter. Most of the upright vegetative tillers on grassland ecosystems during the autumn will be carryover tillers which will resume growth as lead tillers during the next growing season. Almost all grass tillers live for two growing seasons, the first season as vegetative secondary tillers and the second season as lead tillers. Grazing carryover tillers after mid October causes the termination of a large proportion of the population, resulting in greatly reduced herbage biomass production in subsequent growing seasons. The pasture grazed first in the rotation sequence is the last pasture grazed during the previous year. The last pasture grazed has the greatest live herbage weight on 1 June of the following season (Manske 2018b).

Stocking rates are based on peak herbage biomass on seasonlong grazing practices. The starting stocking rate on the "new" twice-over grazing practice is usually 80% to 100% of the seasonlong stocking rate. It usually requires three grazing seasons with the twice-over strategy stocked at 100% to increase the rhizosphere microbe biomass to be great enough to mineralize 100 lbs/ac of mineral nitrogen (nitrate NO_3 and ammonium NH_4). After the increased rhizosphere microbe biomass can mineralize 100 lbs/ac of mineral nitrogen, the stocking rate can be increased at 10% per year until the system is stocked at 140% of the seasonlong stocking rate. This has been the maximum biological potential reached on North American grasslands from the twice-over rotation strategy.

The amount of mineral nitrogen can be measured. Collect a soil core from silty soil at 0 to 12 and 12 to 24 inch depth during mid May from two or three locations in the entire system. Have a soil laboratory analyze for both nitrate NO_3 and ammonium NH_4. The total mineral nitrogen should equal 100 lbs/ac or greater.

Once a rotation date scheduled has been determined, do not change that schedule greater than one day for any worldly reason. If you do not like your neighbors bull, build a fence that the bull cannot jump. If you have water sources that sometimes go dry, put in a water tank system on a pipeline. Fix the problems that develop with solutions that do not change the rotation schedule.

Table 6. Cool season grasses, weekly percent crude protein, percent phosphorus, and phenological growth stages of ungrazed lead tillers in western North Dakota, 1946-1947.

Sample Date	Crude Protein %	Phosphorus %	Phenological Growth Stages
Apr 1			
13	20.5	0.315	Early leaf greenup
19	23.5	0.346	
25	23.0	0.320	
May 4	21.5	0.301	Active leaf growth
10	18.3	0.303	
16	18.2	0.276	Flower stalk developing
23	16.1	0.239	
28	16.6	0.237	
Jun 6	15.1	0.253	Flower stalk emerging
13	14.4	0.258	
19	15.1	0.244	Flowering (anthesis)
26	12.2	0.232	
Jul 2	11.5	0.228	Seed developing
8	10.3	0.205	Seed maturing
16	10.3	0.203	Seed mature
24	8.3	0.186	Seed shredding
30	8.0	0.177	
Aug 6	6.8	0.149	
13	6.9	0.157	Drying
20	6.7	0.153	
26	6.5	0.141	
Sep 3	5.7	0.124	Drying
12	4.9	0.119	
21	-	-	
29	6.4	0.120	Drying
Oct			
Nov 5	4.9	0.116	Drying

Data from Whitman et al. 1951.

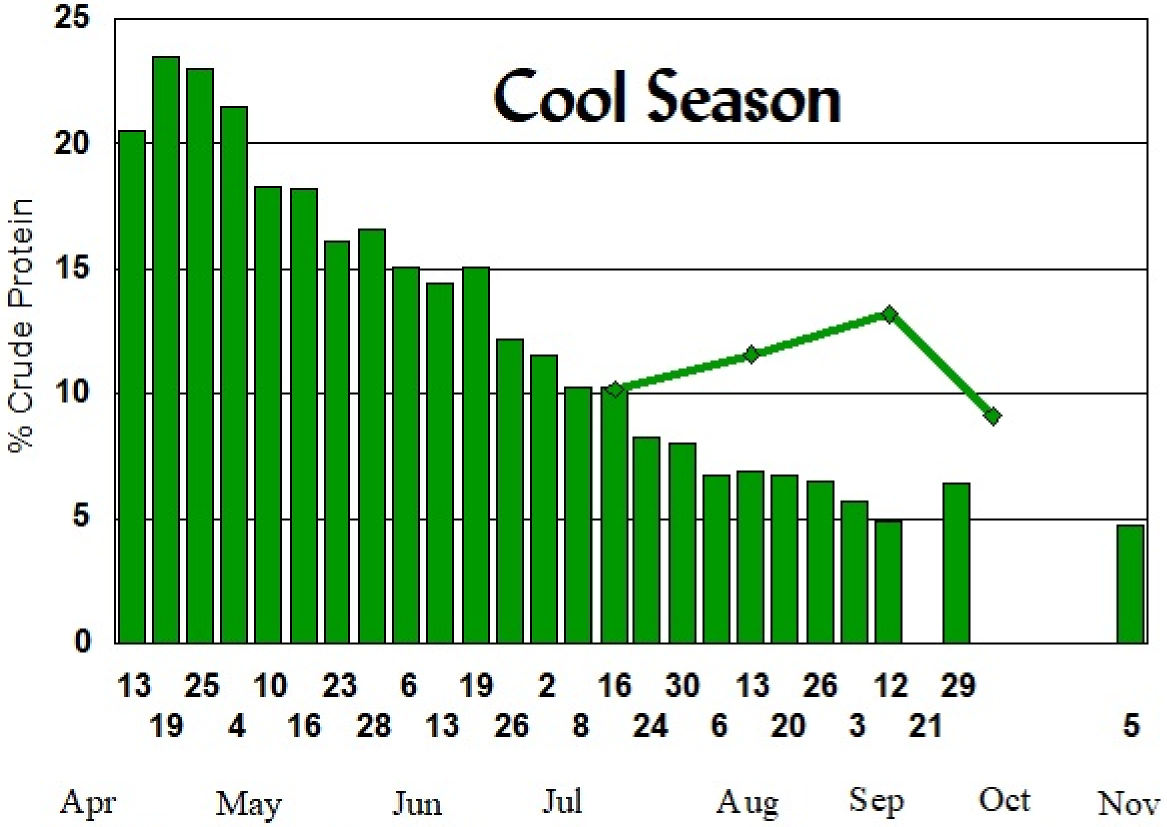

Fig 3. Mean percent crude protein of ungrazed native range cool season grasses in western North Dakota, data from Whitman et al. 1951 and secondary tiller data from Sedivec 1999.

Table 7. Warm season grasses, weekly percent crude protein, percent phosphorus, and phenological growth stages of ungrazed lead tillers in western North Dakota, 1946-1947.

Sample Date	Crude Protein %	Phosphorus %	Phenological Growth Stages
Apr 1			
13			
19			
25			
May 4			
10	15.5	0.267	Early leaf greenup
16	14.7	0.226	
23	15.7	0.232	
28	15.5	0.264	
Jun 6	13.9	0.299	Active leaf growth
13	13.9	0.286	
19	12.3	0.286	
26	12.2	0.275	
Jul 2	11.3	0.245	Flower stalk developing
8	10.4	0.245	Flower stalk emerging
16	9.6	0.222	Flowering (anthesis)
24	9.7	0.226	
30	7.2	0.208	
Aug 6	7.1	0.175	Seed developing
13	7.4	0.186	
20	6.9	0.194	Seed maturing
26	6.2	0.150	
Sep 3	6.4	0.153	Seed mature
12	5.7	0.121	
21	4.8	0.189	Drying
29	4.1	0.076	
Oct			
Nov 5	4.7	0.085	Drying

Data from Whitman et al. 1951.

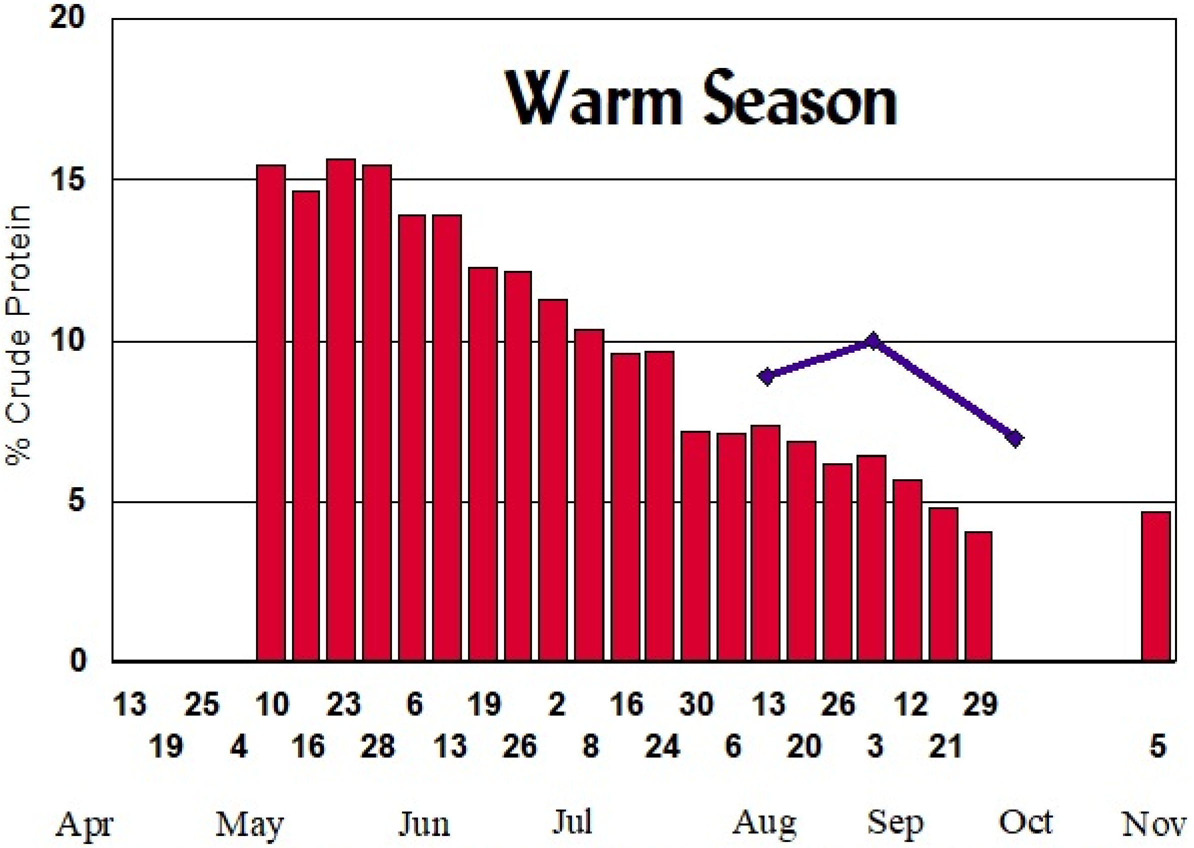

Fig 4. Mean percent crude protein of ungrazed native range warm season grasses in western North Dakota, data from Whitman et al. 1951 and secondary tiller data from Sedivec 1999.

Table 8. Upland sedges, weekly percent crude protein, percent phosphorus, and phenological growth stages of ungrazed lead tillers in western North Dakota, 1946-1947.

Sample Date	Crude Protein %	Phosphorus %	Phenological Growth Stages
Apr 1			
13	14.6	0.270	Flower stalk developing
19	22.2	0.317	
25	15.1	0.210	Flowering (Anthesis)
May 4	15.3	0.210	Seed developing
10	13.2	0.185	
16	15.0	0.170	
23	13.7	0.176	
28	13.8	0.162	Seed maturing
Jun 6	12.9	0.160	
13	14.2	0.160	Seed mature
19	11.3	0.179	
26	12.1	0.152	
Jul 2	11.0	0.153	Drying
8	9.7	0.155	
16	9.8	0.128	
24	8.4	0.122	
30	8.4	0.115	
Aug 6	8.0	0.097	Drying
13	7.5	0.109	
20	7.1	0.118	
26	8.0	0.091	
Sep 3	9.6	0.135	Drying
12	6.3	0.085	
21	-	-	
29	6.8	0.083	
Oct			
Nov 5	6.9	0.096	Drying

Data from Whitman et al. 1951.

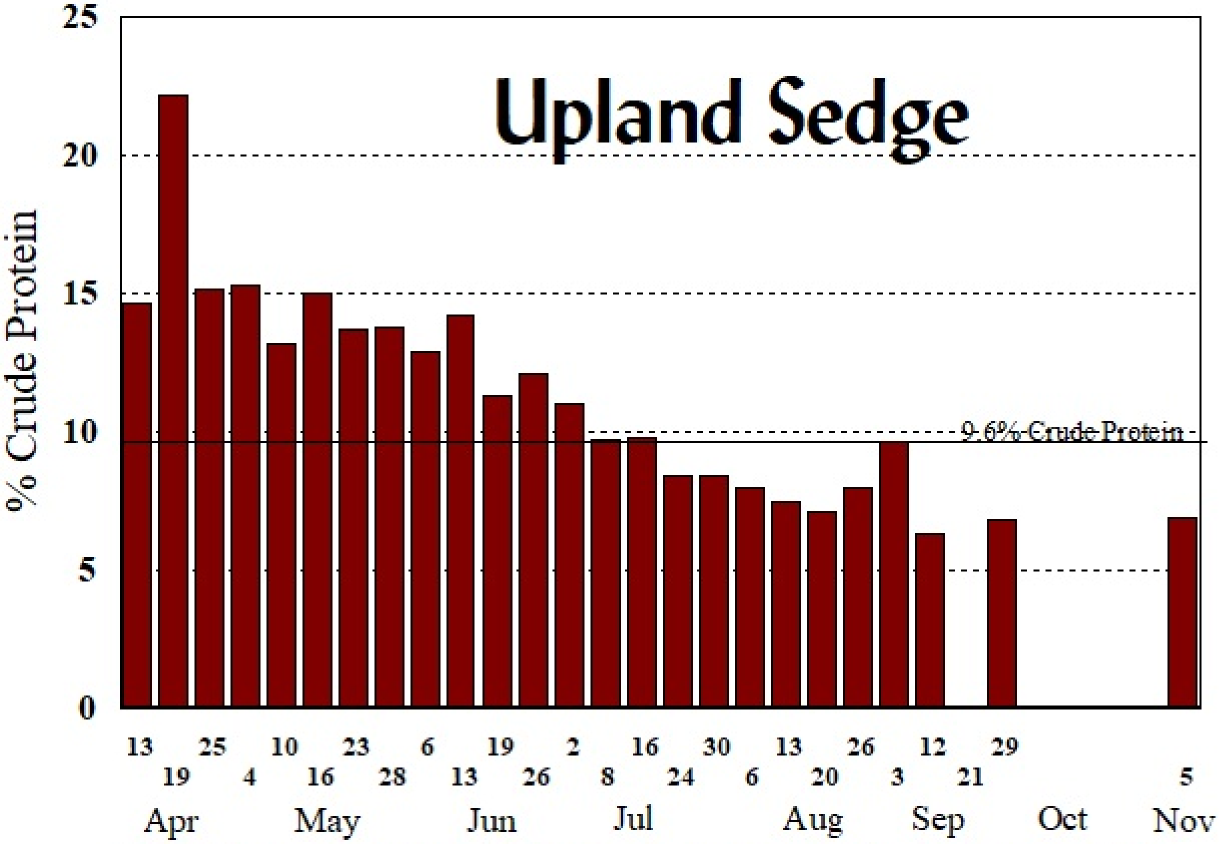

Fig 5. Mean percent crude protein of ungrazed native range upland sedges in western North Dakota, data from Whitman et al. 1951.

Table 9. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Biologically Effective concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	397.73	637.66	760.51	670.20	826.89	698.80
Warm Season	179.90	217.06	304.43	333.21	300.86	302.53
Upland Sedge	165.99	199.29	204.99	175.74	127.28	137.21
Forbs	145.26	146.55	193.27	187.79	164.72	159.88
Grasses	577.63	854.72	1064.94	1003.41	1127.75	1001.33
Graminoids	743.62	1054.01	1269.93	1179.15	1255.03	1138.54
Total	888.88	1200.56	1463.20	1366.94	1419.75	1298.42

Table 10. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Traditional concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	308.46	483.96	606.10	515.39	548.70	542.12
Warm Season	123.98	157.64	244.45	287.08	222.68	241.69
Upland Sedge	168.26	226.16	237.83	222.50	151.45	126.55
Forbs	166.47	218.24	293.73	253.01	212.18	216.13
Grasses	432.44	641.60	850.55	802.47	771.38	783.81
Graminoids	600.70	867.76	1088.38	1024.97	922.83	910.36
Total	767.17	1086.00	1382.11	1277.98	1135.01	1126.49

Table 11. Basal cover (%) of graminoids on the silty sites of the Biologically Effective and Traditional concepts, 1983-2012.

	Biologically Effective		Traditional		
Silty Site	Basal Cover %	Composition %	Basal Cover %	Composition %	Difference %
Cool Season	7.02	24.6	5.85	28.5	20.0
Warm Season	15.95	55.9	8.76	42.6	82.1
Upland Sedge	5.55	19.5	5.95	28.9	-6.7
Grasses	22.97	80.5	14.61	71.1	57.2
Graminoids	28.52		20.56		38.7

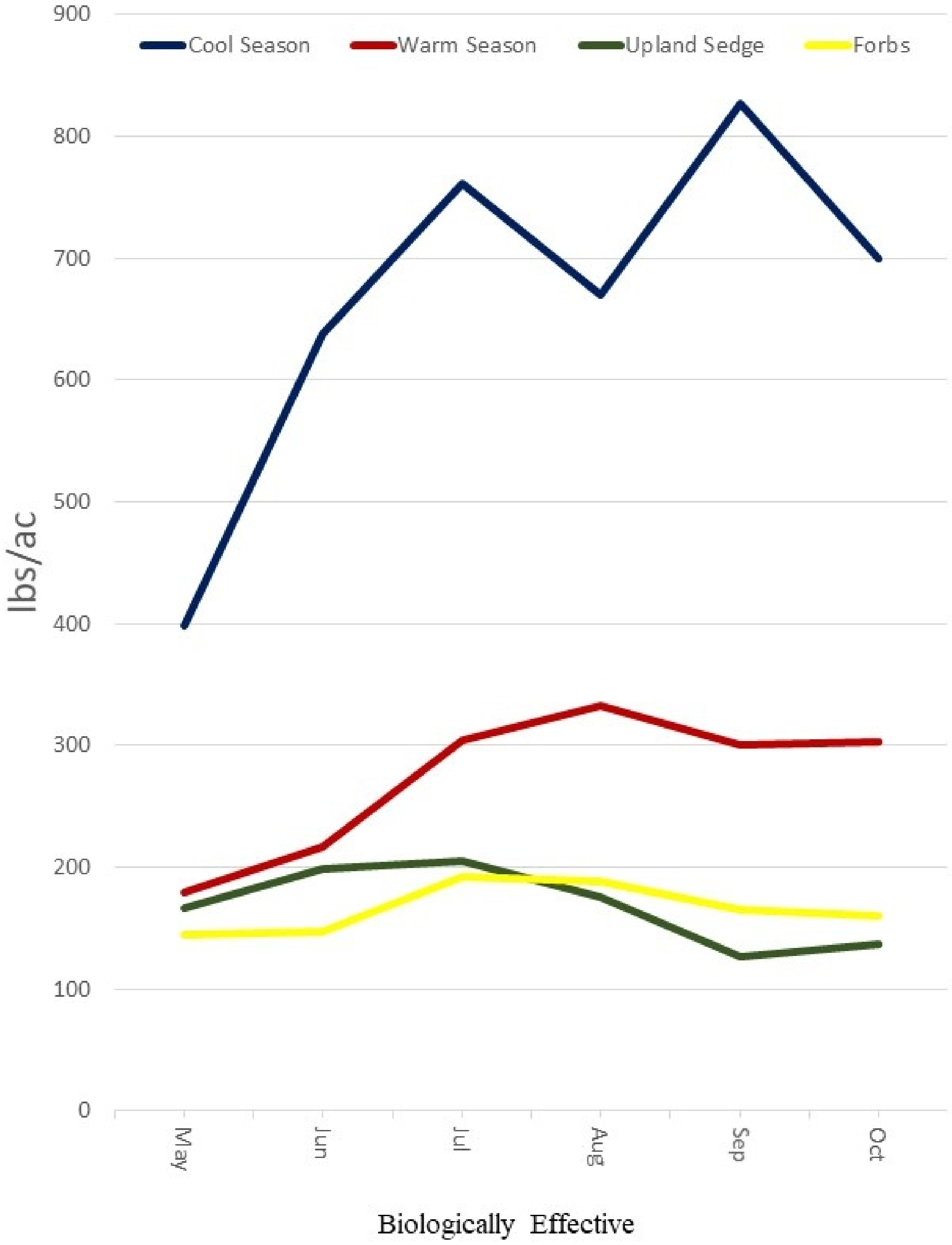

Figure 6. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Biologically Effective concept, 1983-2012.

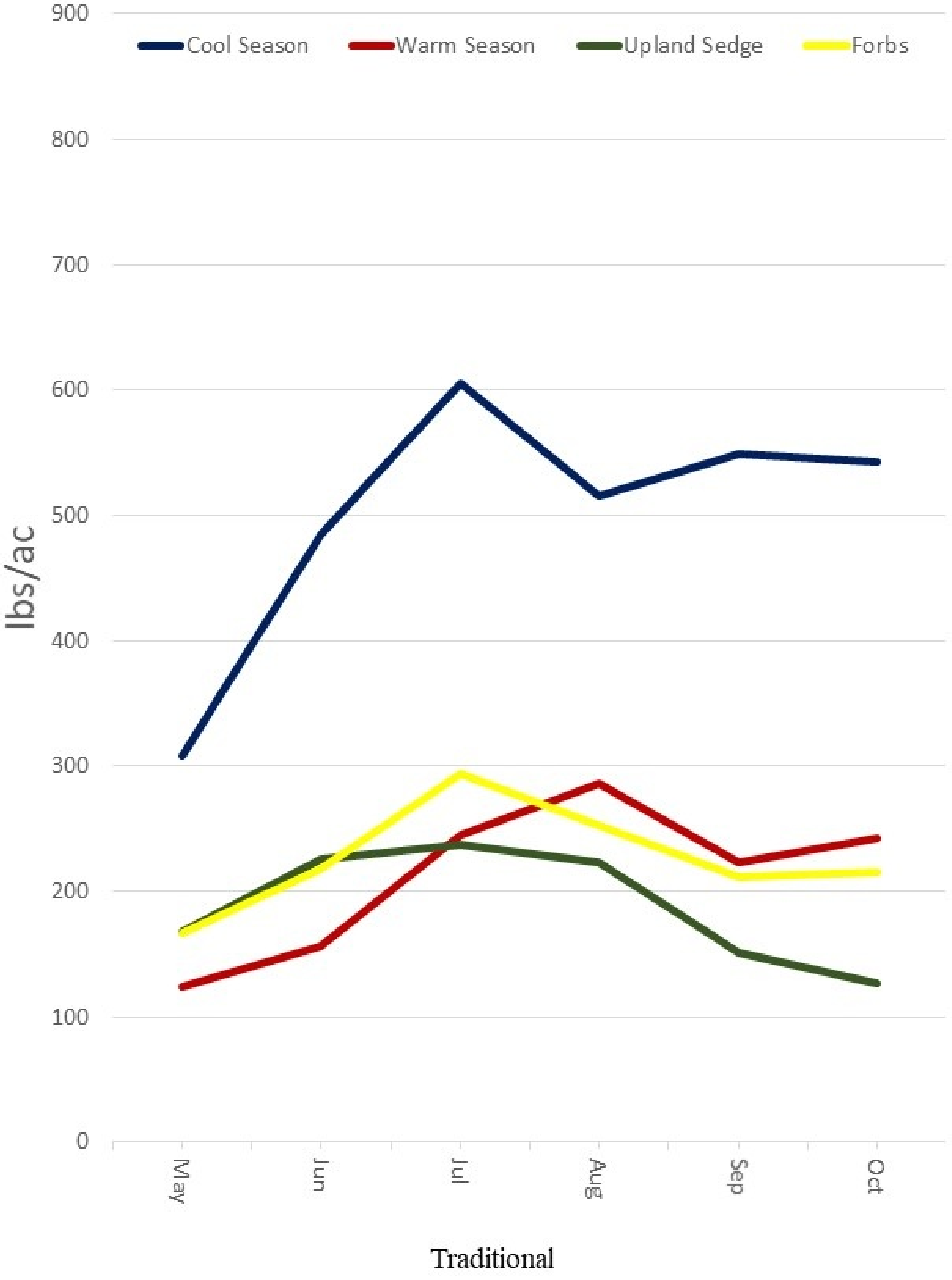

Figure 7. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Traditional concept, 1983-2012.

Table 12. Summer grazing period, stocking rate, and pasture cost on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per C-C pr	Acres per AUM	Pasture Cost $	Cost per day $
Biologically Effective	1 Jun-14 Oct	135	4.43	10.22	2.26	89.53	0.66
Traditional	1 Jun-14 Oct	135	4.43	11.43	2.58	100.13	0.74
% Difference	same	same	same	-10.59	-12.40	-10.59	-10.81

Table 13. Summer cow and calf weight performance and net returns on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Calf Gain $
Biologically Effective							
Calf	380.47	2.89	37.66	266.33	176.80	17.30	0.24
Cow	86.92	0.66	8.68				
Traditional							
Calf	354.37	2.65	30.61	248.06	147.93	12.94	0.28
Cow	67.11	0.50	5.91				
% Difference							
Calf	7.37	9.06	23.03	7.37	19.52	33.69	-14.29
Cow	29.52	32.00	46.87				

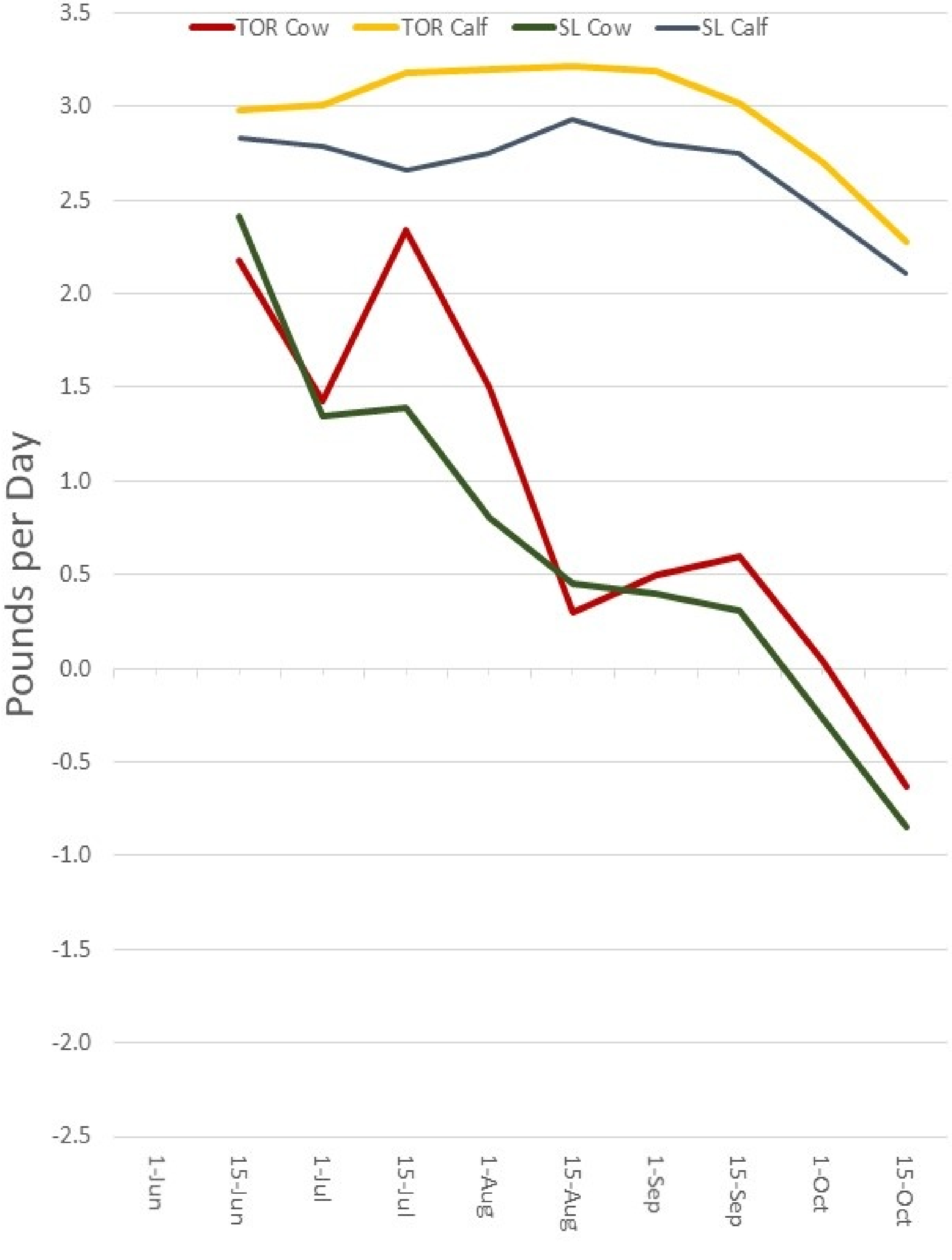

Figure 8. Cow and calf daily gain on the seasonlong and twice-over grazing systems.

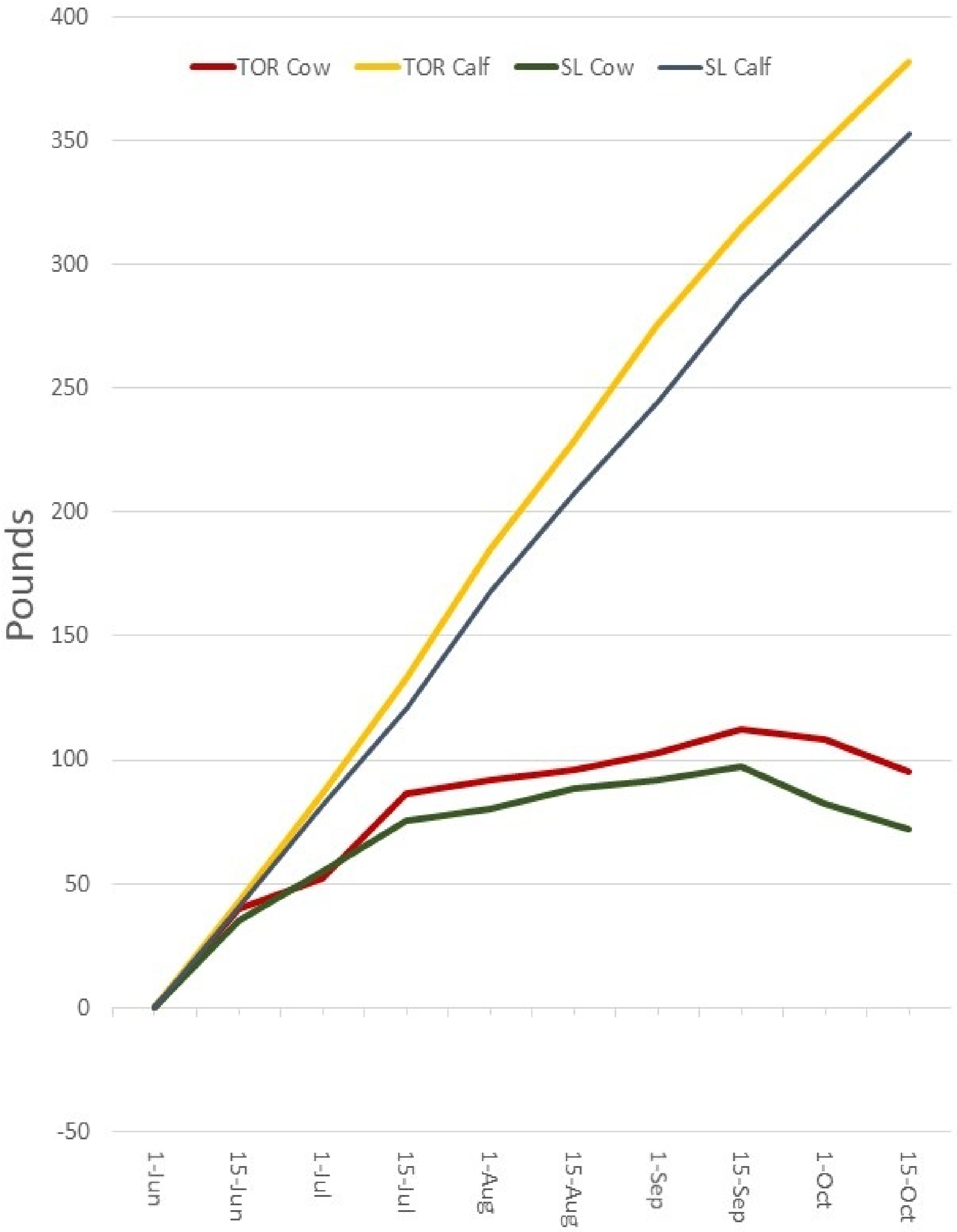

Figure 9. Cow and calf accumulated weight gain on the seasonlong and twice-over grazing systems.

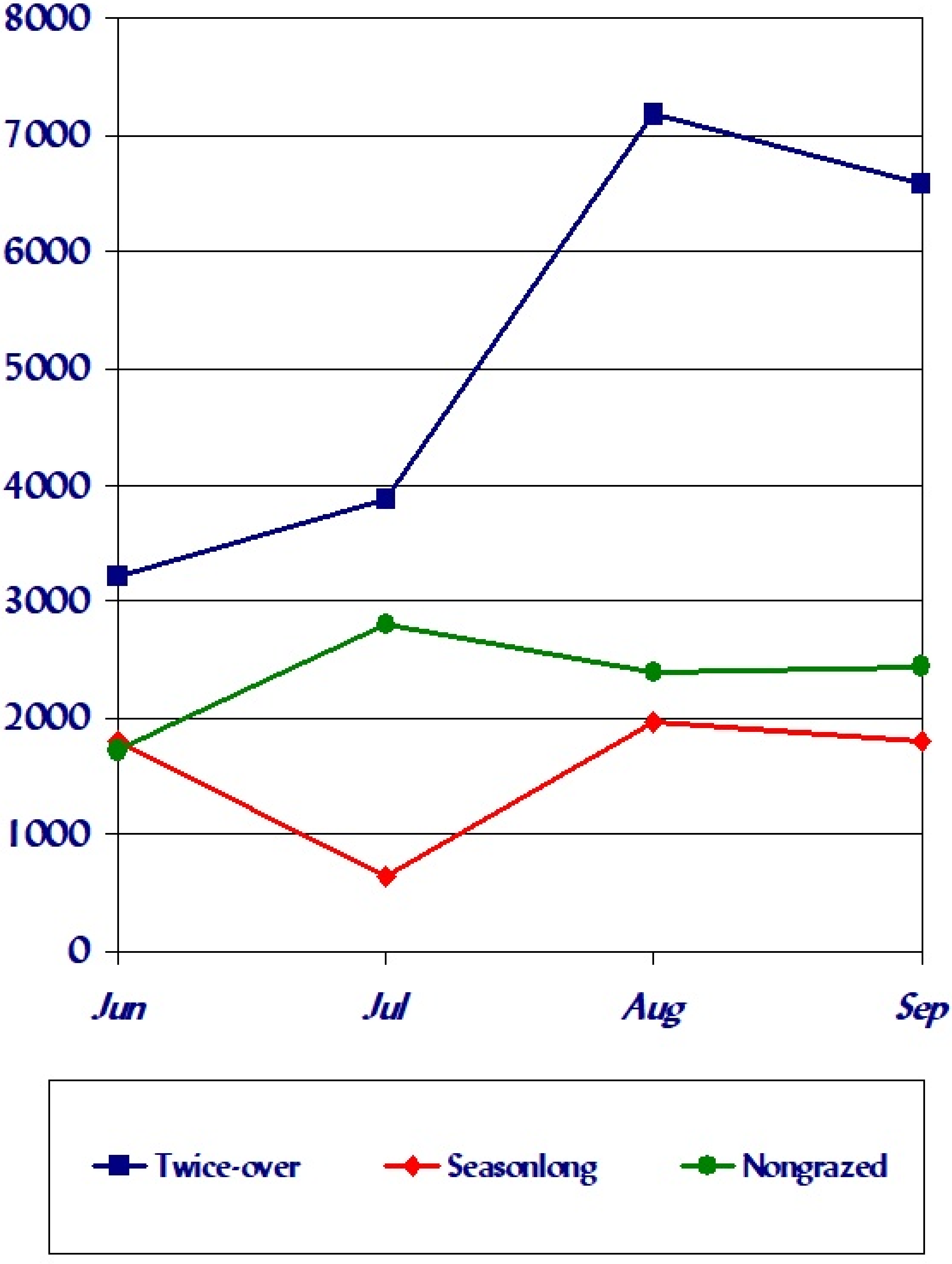

Figure 10. Rhizosphere volume (cm^3) per cubic meter of soil

Table 14. 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.

Table 15. Rhizosphere biomass categories associated with mineral nitrogen biomass categories,

Management Strategy Concept	Biomass Category	Rhizosphere Biomass (microbes, roots, adhered soil)	Mineral Nitrogen Biomass (threshold at 112 kg/ha (100 lbs/ac)	
		kg/m^3	kg/ha	(lbs/ac)
Nongrazed	Very low	52 to 118	15.1 to 27.0	(13.5 to 24.1)
Traditional	Low	104 to 171	26.3 to 65.2	(23.5 to 58.2)
Biologically Effective	High	214 to 406	111.3 to 176.3	(99.4 to 157.4)

Rhizosphere Biomass Not Linearly Related to Mineral Nitrogen Biomass.

Fall Complementary Pastures

The wildryes are the only perennial grass type that retains adequate nutritional quality to meet a lactating cows requirements during fall grazing from mid October to mid November. Despite these unique important characteristics, wildryes are not a popular fall pasture in the Northern Plains. The problem isn't the grasses. The problem is the management. The wildryes do not grow and behave like native grasses of the Northern Mixed Grass Prairie and cannot be managed with the same techniques that the native grasses are managed. The native grasses plus crested wheatgrass and smooth bromegrass grow and behave as if they were types of perennial spring wheat. The wildrye grasses grow and behave as if they were types of perennial winter wheat. Proper management of wildrye fall pastures must be adjusted to accommodate these differences in growth and behavior.

There are numerous types of wildryes in the world. The two common types in the Northern Plains are Altai and Russian Wildryes.

Altai wildrye, *Leymus angustus* (Trin.) Pilg., is a member of the grass family, Poaceae, tribe, Triticeae, syn.: *Elymus angustus* Trin., and is a long lived perennial, monocot, cool-season, mid grass, that is drought tolerant, very winter hardy, highly tolerant of saline soils nearly at the level of tall wheatgrass, and fairly tolerant of alkaline soils. Altai wildrye was introduced into Canada as two seed lots. The first seed lot arrived in 1934 from Voronezh, USSR, located in the far western European Russian Steppe. The second seed lot arrived in 1939 from the Steppe of Kustanay located in the northern region of Kazakhstan. Three synthetic strains were developed from seed increase plots started in 1950 at the Swift Current Research Station followed by more sites at seven research stations in Alberta, Manitoba, and Saskatchewan, which produced the first released cultivar, Prairieland, in 1976. Seed from the increase fields at Swift Current was used to establish 60 acres of Altai wildrye monoculture at the NDSU Dickinson Research Extension Center for a replicated study of late season grazing during mid October to mid November conducted from 1983 to 2005 for 23 years. Early aerial growth consists of basal leaves from crown tiller buds. Basal leaf blades are 15-25 cm (6-10 in) long, 0.5-0.7 cm wide, erect, coarse, light green to bluegreen to blue, and can remain upright under deep wet snow. The leaf sheath is usually shorter than the internodes and grayish green. The membrane ligule is 0.5-1.0 mm long with an obtuse apex. Some early specimens of introduced strains showed vigorous rhizome charateristics and aggressive spreading which was considered to be undesirable. The available released plant material are generally weakly rhizomatous with short rhizomes. Unfortunately, fields seeded with plant material that has nonaggressive short rhizomes is limited by around a 20 to 25 year life expectancy. However, the uniquely deep extensive fibrous root system that can penetrate to depths of 3-4 m (9.8-13.1 ft) and efficiently absorb available soil water was retained. Regeneration is primarily asexual propagation by crown and short rhizome tiller buds. Seedlings have slow, weak growth and are successful only when competition from established plants is nonexistant. Flower stalks are erect, 60-100 cm (24-39 in) tall, mostly leafless and few in numbers. Inflorescence is a terminal spike 15-20 cm (6-8 in) long, 1 cm in diameter, that has closely spread overlapping spikelets of 2 or 3 florets, with 2 or 3 spikelets per node. Basal leaves are palatable to livestock and seed stalks are not. Wildryes maintain slightly higher levels of protein and digestibility with advancing maturity better than other species of perennial grasses. Wildryes are best used for late season grazing from mid October to mid November. Fire top kills aerial parts and kills deeply into the crown when soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reduction in biomass production and tiller density. This summary information on growth development and regeneration of Altai wildrye was based on works of Lawrence 1976, and St. John et al. 2010.

Russian wildrye, *Psothyrostachys juncea* (Fisch.) Nevski., is a member of the grass family, Poaceae, tribe, Triticeae, syn.: *Elymus junceus* Fisch., and is a long lived perennial, monocot, cool-season, mid grass, that is exceptionally drought tolerant, tolerant of extremely cold temperatures, highly tolerant of saline soils, fairly tolerant of alkaline soils, intolerant of spring flooding or high water tables, and does not perform well on sandy soils. Russian wildrye was introduced into the United States from Siberia. It was brought to North Dakota in 1907, grown at the Dickinson Research Extension Center in 1913, and grown at the USDA-ARS at Mandan, ND. in 1927. It was introduced into Canada from Siberia in 1926. Early aerial growth consists of basal leaves from crown tiller buds. Basal leaf blades are 7-40 cm (3-16 in) long, 2-6 mm wide, soft, lax, numerous and dense. The split sheath has overlapping margins and open at the top. Previous years sheath bases are persistent and shredded into fibers. The collar is broad and continuous. The membrane ligule is 1 mm long with a blunt flat edge that has numerous small irregular cuts. The small auricles are 2 mm long, clasping, and clawlike. Some plants form no rhizomes, while other plants have several short rhizomes, while other plants have several short rhizomes that form clumps 20-30 cm (8-12 in) wide. Unfortunately, fields seeded with plant material that has nonaggressive short rhizomes is limited by around a 20 to 25 year life expectancy. All bunches have an extensive network of dense, fibrous roots with a lateral spread of 1.2-1.5 m (4-5 ft) that descend downward to 2.5-3.0 m (8-10 ft) deep. About 75% of the root biomass is in the top 15-61 cm (6-24 in) of soil that provides high plant competition to most other species. Regeneration is primarily asexual propagation by crown and short rhizome tiller buds. Seedlings are weak, develop slowly and are successful only when competition from established plants is nonexistant. Flower stalks are erect, hollow, 60-100 cm (24-39 in) tall, mostly leafless and few in number. Inflorescence is a terminal spike 6-11 cm (2.4-4.3 in) long, 5-9 mm wide, that has closely spaced overlapping spikelets of 1 to 4 florets, with 2 or 3 spikelets per node. Flower period in the Great Plains is May and June. Basal leaves are palatable to livestock and seed stalks are not. Wildryes maintain slightly higher levels of protein and digestibility with advancing maturity better than other species of perennial grasses. Wildryes are best used for late season grazing from mid October to mid November. Fire top kills aerial parts and kills deeply into the crown when soil is dry. Fire halts the processes of the four major defoliation resistance mechanisms and causes great reduction in biomass production and tiller density. This summary information on growth development and regeneration of Russian wildrye was based on works of Stevens 1963, Dodds 1979, Great Plains Flora Association 1986, Ogle et al. 2005, Taylor 2005, and Johnson and Larson 2007.

Wildryes Require Different Management Practices

Growth characteristics of Altai wildrye is quite different from native cool season grasses. Grazing cool season native grasses during vegetative growth stage prior to the flower stage activates vegetative tiller development from axillary buds. Lightly grazing of Altai wildrye prior to the flower stage did not activate vegetative tillers. Early season grazing actually decreased tiller basal cover. However, fall grazing during mid October to mid November that removed 50% or less of the standing leaf biomass greatly increased vegetative secondary tillers and fall tillers that develop during the following summer and early fall.

During early spring, the carryover tillers that survived the winter in the 50% residual herbage biomass of Altai wildrye tussocks regreened providing most of the carbohydrates and energy used for growth of the current leaves of the new seasons lead tillers. Removal of most of the herbage biomass during the fall grazing period causes termination of a major portion of the living crown tillers with greatly reduced active lead tiller growth and critical reductions in herbage biomass and nutritional quality the following growing season.

Lead tillers produce 3.5 new leaves around early June. The seed stalks develop early and are visible before 21 June. The carryover leaves senescence during June. Most of the aboveground herbage biomass weight in June (1668.80 lbs/ac) is the new leaves and stalks of the current lead tillers (figure 11). After the flower stage, the crude protein content of the lead tillers starts to decrease slowly. The vegetative tillers, that have been activated during the previous fall grazing period, begin visible growth shortly after the lead tillers reach the flower stage. The aboveground herbage biomass during July (2210.59 lbs/ac) and August (2291.83 lbs/ac) is the slowly senescent lead tillers and the rapidly growing vegetative tillers. From mid August to about mid October, the fall tillers develop and produce the additional herbage biomass during September (3021.91 lbs/ac) and October (3140.89 lbs/ac). By mid October, the fall tillers should have around 10% to 12% crude protein, the vegetative tillers should have around 10% to 8% crude protein, and the lead tillers should have 8% to 6% crude protein. The ratio of the three tiller types would effect the mean crude protein level of the Altai wildrye forage during the fall grazing period from mid October to mid November (table 16, figure 11).

The lead tillers terminate at the end of their second growing season, the year they produce a seed head. The vegetative tillers carryover during the winter and become the next seasons lead tillers. The fall tillers carryover during the winter and become the next seasons vegetative tillers, a few well developed fall tillers may become lead tillers. The survival of the carryover vegetative tillers and fall tillers depends on the amount of leaf area they retain at the end of the fall grazing period. When 50% or more of the aboveground herbage remains on mid November (1500.00 lbs/ac), most of the vegetative tillers and fall tillers survive to the next spring. However, when greater than 50% of the aboveground herbage is removed by mid November or during an injudicious longer grazing period after mid November, most of the vegetative tillers and fall tillers will have lost greater leaf biomass than they can recover from, resulting in an extremely low survival rate and a rapidly degrading wildrye stand. This devastating reduction in herbage biomass has been incorrectly blamed unto the grass, not on the management practice that truly caused the reductions.

The wildryes do not increase vegetative tiller growth by light grazing during the early vegetative growth stages of lead tillers before the flower stage. So do not graze wildryes during May or June. Vegetative secondary tillers and fall tillers are stimulated by fall grazing from mid October to mid November. There is no data of grazing stimulation during mid September to mid October. We know that grazing from mid October to mid November works when 1500 lbs/ac residual herbage remain from mid November to spring. That seems like a lot of herbage to leave. Remember that at least 1500 lbs/ac of forage is available to be removed. If the 50% quantity of residual is not remaining at the end of the fall grazing period, the quantity of herbage produced for the next fall grazing period will be much less than the potential 3000 lbs/ac, plus a loss of a potential 1000 lbs/ac to 2000 lbs/ac in additional herbage that could be produced when the grasses remain healthy. The residual of 1500 lbs/ac must remain or your management will fail the vegetation, the stand will deteriorate in 20 to 25 years, and the grass receives the blame. By leaving 50% residual annually, the wildrye stand life expectancy could be perpetual. This will require another long-term research study.

Performance of Grass and Livestock

Altai wildrye is an excellent fall pasture during mid October to mid November. The wildryes have been considered to be difficult to grow because they respond differently than the native grasses and common domesticated grasses to standard grassland practices. The wildryes are different and require different management practices. The wildryes are not the problem. The standard management practices are the problem. With 27 years of research, the problems with the standard practices can be corrected.

Four different forage sources for fall complementary pastures have been evaluated that compared two perennial grass forage types and compared two cropland forage types. Two biologically effective fall complementary pastures are Altai wildrye (perennial grass) and Spring Seeded Winter Cereal (cropland). Two traditional fall pastures are Native Rangeland (perennial grass) and Cropland Aftermath (cropland).

The biologically effective fall complementary perennial grass pasture was Altai wildrye. Cow and calf pairs grazed one pasture of Altai wildrye (replicated two times) at 1.41 ac/AUM for 30 days (1.39 ac/AU) from mid October to mid November (table 17).

The traditional fall complementary perennial grass pasture was native rangeland. Cow and calf pairs grazed one pasture of native rangeland (replicated two times) at 4.11 ac/AUM for 30 days (4.04 ac/AU) from mid October to mid November (table 17).

The one pasture traditional concept of native rangeland provided 891 lbs/ac herbage during the mid October to mid November grazing period leaving a residual of 668 lbs/ac, which would indicate a utilization rate of 223 lbs/ac. There is no new growth of native rangeland after mid October and leaf senescence is greatly accelerated, with nutritional quality below a lactating cows crude protein requirements.

The one pasture biologically effective concept of Altai wildrye provided 3141 lbs/ac herbage during the mid October to mid November grazing period leaving a residual of 1496 lbs/ac, which would indicate a utilization rate of 1645 lbs/ac. The residual herbage would include highly senescent lead tiller leaves that would contain 8% to 6% crude protein, secondary vegetative tiller leaves that would contain 10% to 8% crude protein, and fall tiller leaves that would contain 12% to 10% crude protein. Some of the residual would contain the totally senescent seed heads of which the cows do not consume.

On the Altai wildrye strategy, calf weight gain was 1.82 lbs per day, 37.12 lbs per acre, and accumulated weight gain was 50.34 lbs per head. Cow weight gain was 1.62 lbs per day, 32.22 lbs per acre, and accumulated weight gain was 42.60 lbs per head (table 18).

On the native rangeland strategy, calf weight gain was 0.59 lbs per day, 4.38 lbs per acre, and accumulated weight gain was 17.73 lbs per head. Cow weight loss was 1.74 lbs per day, 12.90 lbs per acre, and accumulated weight loss was 52.20 lbs per head (table 18).

Cow and calf weight performance on the Altai wildrye strategy was greater than those on the native range strategy. The calf weight gain per day was 208.47% greater, gain per head was 183.93% greater, and gain per acre was 747.49% greater. The cow weight gain per day was 193.10% greater, gain per head was 181.61% greater, and gain per acre was 349.77% greater (table 18).

Pasture costs were 65.58% lower and cost per day were 65.25% lower on the Altai wildrye strategy than those on the native range strategy (table 17). The dollar value captured was greater on the Altai wildrye strategy, pasture weight gain value was 183.96% greater, net return per cow-calf pair was 200.35% greater, and net return per acre was 391.56% greater, while cost per pound of calf gain was 87.94% lower, than those on the native range strategy (table 18).

The biologically effective fall complementary cropland pasture was spring seeded winter cereal. Cow and calf pairs grazed four pastures of spring seeded winter rye with each pasture grazed for one week (replicated two times) at 0.48 ac/AUM for 30 days (0.47 ac/AU) from mid October to mid November (table 19).

The traditional fall complementary cropland pasture was cropland aftermath of annual cereal residue of oat and/or barley stubble. Cow and calf pairs grazed one pasture of cereal residue forage (replicated two times) at 6.74 ac/AUM for 30 days (6.63 ac/AU) from mid October to mid November (table 19).

The one pasture traditional concept of cropland aftermath provided 270 lbs/ac herbage during the mid October to mid November grazing period leaving a residual of 135 lbs/ac, which would indicate a utilization rate of 135 lbs/ac. The nutrient content of stubble from annual cereal harvested for grain is almost nonexistent and lactating cows cannot find forage that meets their crude protein requirements.

The four pasture biologically effective concept of spring seeded winter cereal provided 1908 lbs/ac forage during the mid October to mid November grazing period leaving no standing residual vegetation. The livestock had access to one fresh pasture per week with reuse of previous pastures.

On the spring seeded winter cereal strategy, calf weight gain was 2.00 lbs per day, 127.66 lbs per acre, and accumulated weight gain was 60.00 lbs per head. Cow weight gain was 1.05 lbs per day, 67.02 lbs per acre, and accumulated weight gain was 31.50 lbs per head (table 20).

On the cropland aftermath strategy, calf weight gain was 0.42 lbs per day, 1.90 lbs per acre, and accumulated weight gain was 12.57 lbs per head. Cow weight loss was 1.61 lbs per day, 7.27 lbs per acre, and accumulated weight loss was 48.17 lbs per head (table 20).

Cow and calf weight performance on the spring seeded winter cereal strategy was greater than those on the cropland aftermath strategy. The calf weight gain per day was 376.19% greater, gain per head was 377.33% greater, and gain per acre was 6618.95% greater. The cow weight gain per day was 165.22% greater, gain per head was 165.39% greater, and gain per acre was 1021.87% greater (table 20).

Pasture costs were 48.57% greater and cost per day were 50.00% greater on the spring seeded winter cereal strategy than those on the cropland aftermath strategy (table 19). Even though the pasture costs were higher, the dollar value captured was greater on the spring seeded winter cereal strategy, pasture weight gain value was 377.27% greater, net return per cow-calf pair was 600.00% greater, and net return per acre was 7182.09% greater, while cost per pound of calf gain was 68.57% lower, than those on the cropland aftermath strategy (table 20).

Grazing native rangeland after mid October and grazing cropland aftermath of annual cereal residue stubble are old style traditional forage management practices previously used with low-performance livestock that do not work biologically nor economically with modern high-performance livestock. Both practices are deficient at providing adequate forage quality and inefficient at nutrient capture. The cows lose considerable weight and the calf weight gain is diminutive resulting in negative net returns (tables 18 and 20).

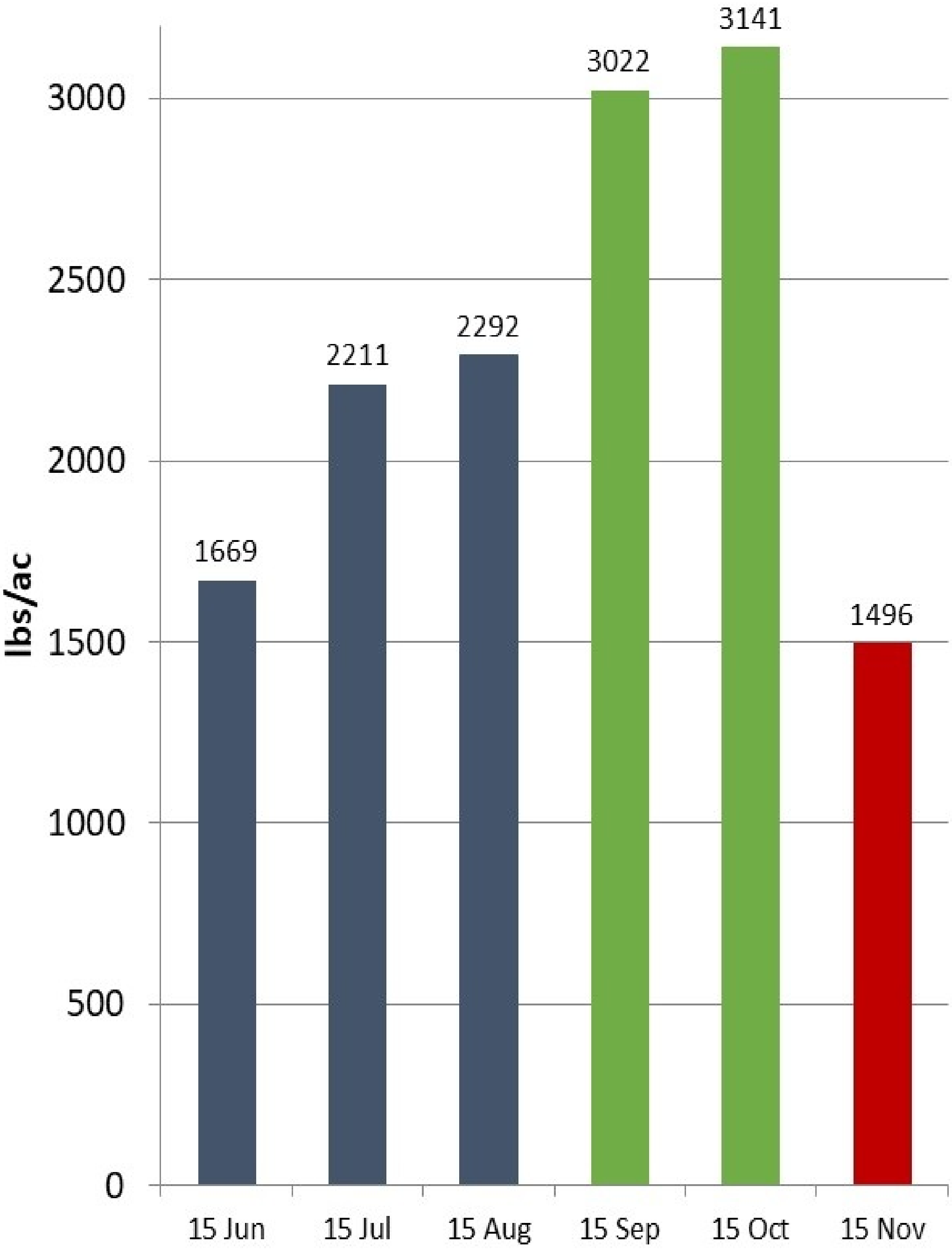

Figure 11. Altai wildrye mean monthly herbage biomass (lbs/ac) on two pastures fall grazed during mid October to mid November, 1984-2002.

Table 16. Conjectural contributions of weight/acre in pounds (lbs) and percentage (%) by the tiller types to total herbage biomass during monthly periods and percent (%) and pounds (lbs) of crude protein from tiller types during the mid October to mid November grazing period.

						Grazing Period	
Tiller Type	Jun	Jul	Aug	Sep	Oct	% CP	lbs CP
Lead Tillers							
lbs/ac	1669	1335	1068	855	684	8%	54.7
%	100.0	60.4	46.6	28.3	21.8		
Secondary Tillers							
lbs/ac		876	1224	1591	1432	10%	143.2
%		39.6	53.4	52.6	45.6		
Fall Tillers							
lbs/ac				576	1025	12%	123.0
%				19.1	32.6		
Total Herbage							
lbs/ac	1669	2211	2292	3022	3141	10.2%	320.9

Table 17. Fall grazing period, stocking rate, and pasture cost on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per C-C pr	Acres per AUM	Pasture Cost $	Cost per day $
Biologically Effective Altai wildrye	14 Oct to 13 Nov	30	0.98	1.39	1.41	12.18	0.41
Traditional Native Rangeland	14 Oct to 13 Nov	30	0.98	4.04	4.11	35.39	1.18
% Difference	same	same	same	-65.59	-65.69	-65.58	-65.25

Table 18. Fall cow and calf weight performance and net returns on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Calf Gain $
Biologically Effective							
Calf	50.34	1.82	37.12	35.24	23.06	16.59	0.24
Cow	42.60	1.62	32.22				
Traditional							
Calf	17.73	0.59	4.38	12.41	-22.98	-5.69	1.99
Cow	-52.20	-1.74	-12.90				
% Difference							
Calf	183.93	208.47	747.49	183.96	200.35	391.56	-87.94
Cow	181.61	193.10	349.77				

Table 19. Fall grazing period, stocking rate, and pasture cost on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Grazing Period	# Days	# Months	Acres per C-C pr	Acres per AUM	Pasture Cost $	Cost per day $
Biologically Effective Spring Seeded Winter Cereal	14 Oct to 13 Nov	30	0.98	0.47	0.48	19.70	0.66
Traditional Cropland Aftermath	14 Oct to 13 Nov	30	0.98	6.63	6.74	13.26	0.44
% Difference	same	same	same	-92.91	-92.88	48.57	50.00

Table 20. Fall cow and calf weight performance and net returns on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept	Gain per Head lbs	Gain per Day lbs	Gain per Acre lbs	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Calf Gain $
Biologically Effective							
Calf	60.00	2.00	127.66	42.00	22.30	47.45	0.33
Cow	31.50	1.05	67.02				
Traditional							
Calf	12.57	0.42	1.90	8.80	-4.46	-0.67	1.05
Cow	-48.17	-1.61	-7.27				
% Difference							
Calf	377.33	376.19	6618.95	377.27	600.00	7182.09	-68.57
Cow	165.39	165.22	1021.87				

Total Pasture Performance of Livestock

The total complementary system evaluated cow and calf weight performance on spring, summer, and fall seasonality pastures managed by two distinctly different concepts; the old style traditional and the modern biologically effective.

On the old style traditional concept, cow and calf pairs grazed one crested wheatgrass spring pasture at 2.14 ac/AU for 28 days during 4 May to 1 June, grazed one summer native rangeland pasture seasonlong at 11.43 ac/AU for 135 days during 1 June to 14 October, and grazed one fall native rangeland pasture at 4.04 ac/AU for 30 days during 14 October to 13 November (table 21). The total complementary system consisted of 17.61 ac/AU grazed for 193 days (6.33 months) from 4 May to 13 November. The total pasture cost was $154.27 per cow-calf pair at a cost per day of $0.80 (table 23). Calf weight gain was 444.77 lbs per head, 2.30 lbs per day, and 25.26 lbs per acre (table 22). Cow weight gain was 74.06 lbs per head, 0.38 lbs per day, and 4.21 lbs per acre (table 22). The gross dollar value captured from calf pasture weight gain was $311.34, net return per cow-calf pair was $157.07, and net return per acre was $8.92, with cost of calf weight gain at $0.50 per lb (table 23).

On the modern biologically effective concept, cow and calf pairs grazed two crested wheatgrass spring pastures in a switchback plan at 1.20 ac/AU for 28 days with each pasture grazed for two alternating 7 day periods during 4 May to 1 June, grazed three summer native rangeland pastures with a twice-over rotation system at 10.22 ac/AU for 135 days with each pasture grazed for two periods per year during 1 June to 14 October, and grazed one Altai wildrye fall pasture at 1.39 ac/AU for 30 days during 14 October to 13 November (table 21). The total complementary system consisted of 12.81 ac/AU grazed for 193 days (6.33 months) from 4 May to 13 November. The total pasture cost was $112.22 per cow-calf pair at a cost per day of $0.58 (table 23). Calf weight gain was 507.26 lbs per head, 2.63 lbs per day, and 39.88 lbs per acre (table 22). Cow weight gain was 204.95 lbs per head, 1.06 lbs per day, and 16.11 lbs per acre (table 22). The gross dollar value captured from calf pasture weight gain was $355.08, net return per cow-calf pair was $242.86, and net return per acre was $18.96, with cost of calf weight gain at $0.22 per lb (table 23).

The spring, summer, and fall grazing periods occurred at the same time, the number of days grazed and the number of months grazed were the same on both concept complementary systems (table 21). The Biologically Effective complementary system grazed 4.8 fewer acres, at $42.05 lower pasture cost per cow-calf pair, and at $0.22 lower cost per day (table 23). On the Biologically Effective concept system, calf weight gain was 62.5 lbs per head greater, at 0.33 lbs per day greater, and at 14.62 lbs per acre greater. Cow weight gain was 130.89 lbs per head greater, at 0.68 lbs per day greater, and at 11.90 lbs per acre greater (table 22). The gross dollar value captured from calf pasture weight gain was $43.74 greater, net return per cow-calf pair was $85.79 greater, and net return per acre was $10.04 greater, with cost of calf weight gain at $0.28 per lb lower (table 23).

A hardworking rancher has 6 sections of land with typical Northern Plains soils and 3840 acres of perennial grass pastures. This rancher firmly believes that the improved genetics of his livestock will enhance the ranches profit margin. He continues to standby the old style traditional management concepts taught to him by his father and grandfather that had pulled the family through many hard times. This land has historically been able to graze 218 cow-calf pairs during a 193 day grazing season on 467 acres of crested wheatgrass in one spring pasture, 2492 acres of summer native rangeland with a seasonlong system, and 881 acres of reserved fall native rangeland in one pasture. The herd gross dollar value captured from the average of 444.77 lbs per calf was $67,872, minus a total pasture cost of $33,631, yields a pasture net return from 218 cow-calf pairs of $34,241.

A neighboring ranch family has 6 sections of land with typical Northern Plains soils and 3840 acres of perennial grass pastures. This two generation ranch family had attended Manske's 3-day grazing workshop in January three years earlier. They now have their pasture land fully implemented with the biologically effective management concept. They have determined that they are able to graze 300 cow-calf pairs during a 193 day grazing season on 360 acres of spring crested wheatgrass with a two pasture switchback plan, 3064 acres of summer native rangeland with a three pasture twice-over system, and 416 acres of fall Altai wildrye in one pasture. The herd gross dollar value captured from the average of 507.26 lbs per calf was $106,524, minus a total pasture cost of $33,666, yields a pasture net return from 300 cow-calf pairs of $72,858. This pasture net return is $38,617 (112.8%) greater than the pasture net returns received from the same type land managed by old style traditional concepts and grazed by identical high-performance modern cow-calf pairs.

Biologically Effective Forage Management Matching Modern Beef Cattle Requirements

Both the old-style traditional concept and the modern biologically effective concept used the same high-performance beef cattle on the same Northern Plains soil types. However, these modern beef cattle did not perform at their genetic potentials when they grazed grassland pastures managed with old style traditional technology that had originally been designed for old-style livestock. Grass lead tillers during the seed development stage drop below the crude protein requirements of lactating cows. This stage occurs during late June for crested wheatgrass, during mid July for native cool season grass, and during late July for native warm season grass and they remain deficient of crude protein during the remainder of the grazing season. Traditional management practices do not stimulate secondary tiller development for herbage growth after mid July. The old-style cows would graze native rangeland during June and early July, put on considerable body fat, and then be able to milk about 6 to 7 lbs/d from that body fat during mid July to mid October. Modern high-performance cows have had the ability to deposit large quantities of body fat genetically removed. The typical quantity of body fat on modern cows can produce milk for about one week. In order for modern cows to perform at their genetic potential, the require quantities of crude protein and energy need to be met everyday.

During each of the three seasonality periods of the spring, summer, and fall pastures of the biologically effective complementary system, the four major grass growth mechanisms and the ecosystem biogeochemical processes were all fully activated by properly coordinated partial defoliation by grazing graminivores.

Full activation of the compensatory physiological mechanisms within grass plants requires the availability of a threshold quantity of 100 lbs/ac of mineral nitrogen, thereafter it, accelerates growth rates of replacement leaves and shoots, increases photosynthetic capacity of remaining mature leaves that increase the quantity of available fixed carbon, increases the uptake of rhizosphere mineralized nitrogen, and increases restoration of biological and physiological processes enabling rapid and complete recovery of partially defoliated grass tillers at a replacement biomass rate of 140% of the grass biomass removed by grazing.

Full activation of the asexual mechanisms of vegetative reproduction by tillering requires the availability of a threshold quantity of 100 lbs/ac of mineral nitrogen, thereafter it, increases secondary tiller development from axillary buds, increased initiated tiller density during the growing season, and increases herbage biomass production, and improves herbage nutritional quality that meets the modern cows crude protein requirements to late September 100% of the years and to mid October 64% of the years.

Full activation of the precipitation (water) use efficiency mechanisms requires the availability of a threshold quantity of 100 lbs/ac of mineral nitrogen, thereafter it, increases herbage biomass production 50.4% per inch of rainfall received and greatly reduces the detrimental effects to grass herbage production during water deficiency periods and during drought conditions.

Full activation of the nutrient resource uptake mechanisms increases root absorption of soil water and the major and minor essential elements, improves the robustness of grass growth and development, increases competitiveness and dominance of healthy grasses, and increases suppression of undesirable grass, weedy forb, and shrub seedlings or rhizome shoots from encroachment and establishment within grassland communities.

A large active biomass from 214 kg/m^3 to 406 kg/m^3 of rhizosphere microorganisms is required to perform the ecosystem biogeochemical processes at potential rates. Biogeochemical processes renew the nutrient flow activities in ecosystem soils of renewable natural resources. Biogeochemical processes transform stored essential elements from organic forms into plant usable inorganic forms. Biogeochemical processes also capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen, with assistance from active live plants, and transform the captured major essential elements into storage as organic forms for later use. Biogeochemical processes decompose complex unusable organic material into compounds and then into reusable essential elements.

With the grass growth mechanisms and ecosystem biogeochemical processes functioning at biological potentials, the three indispensable biotic grassland ecosystem components, grass plants, soil microbes, and grazing graminivores have the opportunity to produce at their biological potentials. The biologically effective management of crested wheatgrass produced 73.1% greater herbage biomass during the grazing period than the traditionally managed crested wheatgrass. The biologically effective management of cool season grass produced basal cover at 20.0% greater, July peak herbage at

25.5% greater, and September peak herbage at 50.7% greater than the traditionally managed cool season grass. The biologically effective management of warm season grass produced basal cover at 82.1% greater, August peak herbage at 16.1% greater, and September and October herbage biomass at 29.9% greater than the traditionally managed warm season grass. The biologically effective management of Altai wildrye produced 252.5% greater herbage during the grazing period than the traditionally managed fall native rangeland pasture.

The biologically effective complementary system produced calf weight gain at 14.1% greater per head, 14.4% greater per day, and 57.9% greater per acre, produced cow weight gain at 176.7% greater per head, 179.0% greater per day, and 282.7% greater per acre than that produced on the traditional complementary system. The biologically effective complementary system produced gross dollar value of calf pasture weight gain at 14.1% greater, net return per cow-calf pair at 54.6% greater, and net return per acre at 112.6% greater, with cost of calf weight gain at 56.0% lower per pound than that produced on the traditional complementary system.

Total Complementary Grazing System

The North American beef production industry guided a major effort to improve beef animal genetic productivity resulting in high-performance beef livestock with greater nutrient demand. Imprudently, the forage management technology to meet these higher nutrient requirements at low cost was not simultaneously improved.

Unfortunately, modern beef cattle do not perform at their genetic potentials on pasture forage managed by old style traditional technology. Which has been clearly illuminated by the results of this study (tables 21, 22, and 23). Traditional forage management practices are deficient at providing adequate forage quality during the entire grazing period, inefficient at nutrient capture and conversion, antagonistic to plant growth mechanisms, and suppressive to ecosystem biogeochemical processes performed by the soil microorganisms.

Biologically effective forage management technology has been developed for high-performance beef livestock and is able to provide the biological and physiological requirements to the forage grass plants, soil microorganisms, and grazing livestock, able to activate and maintain the grass plant growth mechanisms and the ecosystem biogeochemical processes, able to revitalize soil structure and functionality, able to increase forage quantity and nutritional quality, and able to improve livestock growth and performance along with the capture of greater wealth per acre from renewable grassland natural resources.

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Table 21. Total grazing periods, and stocking rates on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept Seasonality Units	Grazing Periods	# Days	# Months	ac/AU	ac/AUM
Biologically Effective					
Spring	4 May-1 Jun	28	0.92	1.20	1.30
Summer	1 Jun-14 Oct	135	4.43	10.22	2.26
Fall	14 Oct-13 Nov	30	0.98	1.39	1.41
Total	4 May-13 Nov	193	6.33	12.81	2.02
Traditional					
Spring	4 May-1 Jun	28	0.92	2.14	2.33
Summer	1 Jun-14 Oct	135	4.43	11.43	2.58
Fall	14 Oct-13 Nov	30	0.98	4.04	4.11
Total	4 May-13 Nov	193	6.33	17.61	2.78
% Difference					
Spring	same	same	same	-43.93	-44.21
Summer	same	same	same	-10.59	-12.40
Fall	same	same	same	-65.59	-65.69
Total	same	same	same	-27.26	-27.34

Table 22. Total cow and calf weight performance on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept Seasonality Units	Gain per Head lbs	Cow Gain per Day lbs	Gain per Acre lbs	Gain per Head lbs	Calf Gain per Day lbs	Gain per Acre lbs
Biologically Effective						
Spring	75.43	2.60	65.49	76.45	2.61	66.60
Summer	86.92	0.66	8.68	380.47	2.89	37.66
Fall	42.60	1.62	32.22	50.34	1.82	37.12
Total	204.95	1.06	16.11	507.26	2.63	39.88
Traditional						
Spring	59.15	2.05	26.67	72.67	2.57	32.93
Summer	67.11	0.50	5.91	354.37	2.65	30.61
Fall	-52.20	-1.74	-12.90	17.73	0.59	4.38
Total	74.06	0.38	4.21	444.77	2.30	25.26
% Difference						
Spring	27.52	26.83	145.56	5.20	1.56	102.25
Summer	29.52	32.00	46.87	7.37	9.06	23.03
Fall	181.61	193.10	349.77	183.93	208.47	747.49
Total	176.74	178.95	282.66	14.05	14.35	57.88

Table 23. Total pasture costs and net returns on the Biologically Effective concept compared to those on the Traditional concept.

Management Strategy Concept Seasonality Units	Pasture Cost $	Cost per Day $	Accumulated Weight lbs	Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Cost/lb Weight Gain $
Biologically Effective							
Spring	10.51	0.38	76.45	53.52	43.00	35.84	0.14
Summer	89.53	0.66	380.47	266.33	176.80	17.30	0.24
Fall	12.18	0.41	50.34	35.24	23.06	16.59	0.24
Total	112.22	0.58	507.26	355.08	242.86	18.96	0.22
Traditional							
Spring	18.75	0.67	72.67	50.87	32.12	15.00	0.26
Summer	100.13	0.74	354.37	248.06	147.93	12.94	0.28
Fall	35.39	1.18	17.73	12.41	-22.98	-5.69	1.99
Total	154.27	0.80	444.77	311.34	157.07	8.92	0.50
% Difference							
Spring	-43.95	-43.28	5.20	5.21	33.87	138.93	-46.15
Summer	-10.59	-10.81	7.37	7.37	19.52	33.69	-14.29
Fall	-65.58	-65.25	183.93	183.96	200.35	391.56	-87.94
Total	-27.26	-27.50	14.05	14.05	54.62	112.56	-56.00

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Advanced Harvested Forage Management Technology for the Northern Mixed Grass Prairie

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

The goals of this study were developed by Dr. Warren C. Whitman (c. 1950) and Dr. Harold Goetz (1963) which were to gain quantitative knowledge of each component part and to provide a pathway essential for the understanding of the whole prairie ecosystem that would result in the development and establishment of scientific standards for proper management of native rangelands of the Northern Plains. The introduction to this study can be found in report DREC 16-1093 (Manske 2016b).

Shortly after the end of World War II, fattening feeder beef animals to finish changed from a forage based ration to primarily a grain based ration (Hutcheson and Eng 2007). A great deal of research and experimentation was dedicated to the development of new technologies needed to properly feed a high energy grain based ration that can cause digestive problems when fed to ruminant beef animals by reducing rumen pH. Also, in order to increase the rate of gain of the feeder beef animals, the genetic constitution of the North American beef herd needed improvement. As a result, beef cows have been transformed into modern high-performance cattle that are larger and heavier, gain weight more rapidly, produce more milk, deposit less body fat, and require greater nutrient intake than the old-style cows. However, superior forage ration management technologies for the modern high-performance beef cow were not simultaneously developed while the new and improved feeder ration technologies were being developed. Modern stocker and feeder producers are severely encumbered by using slightly modified traditional forage management technologies developed for the old-style low-performance livestock.

Livestock agriculture has a lifelong apprenticeship with the basic foundations passed within families from generation to generation. However, this new problem to overcome has not been solved by traditional practices. The genetic code of the North American beef herd has been changed and the modern cow is quite different from the old-style cow. The forage management technologies that worked with the old-style cow do not effectively work with the modern high-performance cow. Some long held traditional paradigms need to be challenged in order to develop new forage management technologies matched to the nutrient requirements of the modern high-performance cows that will permit them to produce at their genetic potentials.

Most beef producers, agricultural loan agents, and ag economists maintain a traditional paradigm that considers the source of wealth from beef production to be the selling of beef weight at market, the same as the source of wealth from wheat or corn production is the selling of the weight of wheat or corn grain at market. However, there is a biological difference. Green plants are autotrophic and use sunlight as a source of energy to synthesize organic material from acquired inorganic substances. Livestock are heterotrophic and consume grass plants as the source of energy and organic substances which are broke down during digestion and then used to synthesize the required organic material. The source of livestock weight is the renewable nutrients and essential elements from consumed plant material produced on the land natural resources. Livestock weight is not self produced.

As a result from retention of other long held traditional paradigms, almost every beef cow-calf producer still has a staunch assumption that feeding harvested forages is expensive and that these excessive costs are the major cause for the high production costs of beef cows. This traditional paradigm has prompted many beef producers to develop nonconventional practices in order to reduce the quantities of harvested forages used. An example rationale, the cash cost for pasture is lower than that for harvested feeds, therefore, late season pasture is cheaper than feeding hay. These nonconventional practices are generally not properly evaluated for costs and returns and often actually increase production costs for a beef cow.

There is a mismatch of forage nutrients required by modern high-performance cows and the forage nutrients provided by traditional low-performance forage management practices. Modern cattle on traditional forage management treatments based on the technologies developed for old-style cattle have reduced production efficiencies that depress cow and calf weight performance below genetic potentials causing reduced value received at market and reduced profits. Improvement of forage management practices that provide the required quantities of forage nutrients at the time they are needed by the cow can enhance cow and calf weight performance to the level of their genetic potential.

A great deal of difference exists for the quantity of energy (TDN) and crude protein required between a 1000 lb old style cow and a modern 1200 lb cow with average milk production or with high milk production (table 1). The modern high production range cow has greater nutrient demand that is not simply proportional to the cows greater size. A high performance 1200 lb range cow with average milk production at 20 lb/d, is 20% larger than an old style 1000 lb range cow that had milk production at 12 to 6 lb/d, and requires 27% more energy and 41% more crude protein per day during the lactation production periods than the old style range cow (table 1). A high performance 1200 lb range cow with high milk production at 30 lb/d requires 43% more energy and 72% more crude protein per day during the lactation periods than the old style range cow (table 1) (Manske 2014a).

The old style range cow could deposit considerable quantities of body fat during June and two or three weeks of July when grass had high levels of crude protein. These large quantities of body fat permitted the old style cows to produce around 6 lb/d of milk during August, September, and two weeks of October. This and other production characteristics of the old style cow gave her the ability to tolerate traditional forage management practices that were negligent in providing forage with adequate amounts of crude protein. Four of the five forage management practices on table 2 are traditional practices that provided forages deficient of crude protein during 45% to 29% of the days in an annual cycle. These traditional forage practices are still being use to provide forage deficient of crude protein to modern cows. However, the modern cow does not have the tolerance characteristics of the old style cow; the modern cow production levels decrease well below her genetic potentials each day when consuming forages deficient of required essential elements. This loss in productivity usually has greater value than the cost savings from low quality forage. The fifth forage strategy on table 2 was designed to provide adequate forage quality to meet the modern cows requirements each day of the year; except for 15 days during 36% of the years, crude protein is deficient. During 64% of the years, crude protein is not deficient (Manske 2018a). The modern cow appears to be able to tolerate one week with gradual decreases from forage deficient of required nutrients, after that her production levels greatly decrease.

Forage management practices with no hay

Raising beef animals without feeding hay is an intriguing proposition to many beef producers and it was actually attempted for a short period during the late 19th century in western North Dakota and eastern Montana. The Northern Pacific Railroad constructed new tracks from Bismarck through Dickinson and into eastern Montana during 1880 and 1881. Buffalo skinners shipped 1.5 million bison hides from the region to eastern markets between 1880 and 1884. Several large herds of light weight 2-4 year old steers and dry cows were trail north from Texas during 1882 and 1883 to be fattened on the open range grasses and then be shipped to eastern markets by rail as live animals or as hanging carcasses. The first regional roundup in western North Dakota was conducted in the spring of 1884 in a district that was 100 by 50 miles with Medora near the center. The population of cattle was estimated to be between 30,000 and 40,000 head at a stocking level of 80 to 100 acres per animal for a year of grazing. During the fall of 1886, the local stockman declared the district to be fully stocked and that no new outfits would be permitted to bring additional cattle or horses onto the range. Then the very severe winter conditions of 1886-1887 occurred with numerous blizzards, very strong winds, and long spells of bitter sub-zero temperatures. By spring, 50% to 75 % of the cattle had been lost. A few outfits had nearly 100% losses. Most of the absentee owned outfits pulled out. A few locally owned and operated outfits remained by maintaining relatively small herd sizes. Financial backers stopped lending money to businesses that engaged in the risky activities of year around grazing to fatten cattle on northern plains open range grasses (Manske 1994).

This five year experimental exploitation of the northern plains grass natural resources ended with a tragic loss of livestock and huge economic losses. The severe weather conditions were not the sole factor responsible for this disaster. These light weight cattle also had to contend with low availability (snow covered) forage having inadequate quantity and quality, frozen water sources, and poor wind breaks. Healthy cattle that are provided an adequate forage ration, liquid water, and protected by good wind breaks can tolerate fairly severe winter weather conditions.

Every winter is not as severe as that of 1886-1887, but some could be. Can modern beef cows and calves be raised profitably in the northern plains on just native rangeland grasses without hay if protected by good wind breaks, and provided access to liquid water and supplemental crude protein? A cooperative producer project evaluation of a 12 month native rangeland management practice with multiple seasonal pastures, without hay, organized as one replication was conducted for most of three years during the early 1980's. A simple data collection protocol included monthly herbage biomass clips, and periodic weights of 20 cows and calves identified by ear tag number.

Even though the data protocol was not followed as planned, the data was significantly complete, with the exception of cow weights, to confidently evaluate a native range forage management practice without hay for costs, returns, and profitability.

Dry Gestation

Reserved native rangeland managed as a repeated seasonal pasture was evaluated during the dry gestation production period for 37 days (table 3). Native rangeland forage during the late fall dormancy period has low crude protein content of around 4.8%. Late-season native rangeland forage has a low pasture rent value or production cost of $8.76 per acre, high forage dry matter cost of $97.33 per ton, and high crude protein cost of $1.01 per pound. A cow grazing during the dry gestation production period requires a large land area of 6.17 acres (5.08 acres per month) at a high forage cost of $54.05 per production period. The crude protein content of mature native rangeland forage is below the requirements of a cow and would need to be supplemented at 1.49 lbs per cow per day at a cost of $16.54 per period. Total feed costs are high at $70.59 per period and $1.91 per day. Calf fetus weight gain was assumed to be 0.73 lbs per day; accumulated weight gain was 27.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $27.00 per calf. The net return after pasture forage costs were a high loss of $43.59 per cow-calf pair and a loss of $7.07 per acre. The extremely high cost of calf fetus weight gain was $2.61 per pound.

Third Trimester

Reserved native rangeland managed as a repeated seasonal pasture was evaluated during the third trimester production period for 90 days (table 3). Native rangeland forage during the winter dormancy period has a low crude protein content of around 4.8%. Late-season native rangeland forage has a low pasture rent value or production cost of $8.76 per acre, very high forage dry matter cost of $120.83 per ton, and extremely high crude protein cost of $1.26 per pound. A cow grazing during the third trimester production period requires a large land area of 18.62 acres (6.31 acres per month) at a extremely high forage cost of $163.11 per production period. The crude protein content of mature native rangeland forage is below the requirements of a cow and would need to be supplemented at 0.43 lbs per cow per day at a cost of $11.61 per period. Total feed costs are extremely high at $174.72 per period and $1.94 per day. Calf fetus weight gain was assumed to be 0.76 lbs per day; accumulated weight gain was 68.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $68.00 per calf. The net return after pasture forage costs were an extremely high loss of $106.72 per cow-calf pair and a moderate loss of $5.73 per acre. The extremely high cost of calf fetus weight gain was $2.57 per pound.

Early Lactation

Reserved native rangeland managed as a repeated seasonal pasture was evaluated during the early lactation production period for 45 days (table 3). Forage on native rangeland pasture during early spring has a crude protein content of around 9.2%, the grass tillers were activating chlorophyll and starting to regreen portions of the carryover leaves. Early spring native rangeland forage has a low pasture rent value or production cost of $8.76 per acre, extremely high forage dry matter cost of $140.16 per ton, and very high crude protein cost of $0.76 per pound. A cow grazing during the early lactation period requires a large land area of 10.80

acres (7.32 acres per month) at a very high forage cost of $94.61 per production period. The crude protein content of early spring native rangeland forage is below the requirements of a cow, however, crude protein was not supplemented. Total feed costs are very high at $94.61 per period and $2.10 per day. Calf weight gain was 1.24 lbs per day; accumulated weight gain was 56.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $56.00 per calf. The net return after pasture forage costs was a very high loss of $38.61 per cow-calf pair and a moderate loss of $3.58 per acre. The very high cost of calf weight gain was $1.69 per pound.

Spring Lactation

Native rangeland managed as a repeated seasonal pasture was evaluated during the spring lactation production period for 28 days (table 3). Native rangeland grass tillers had not reached the three and half new leaf growth stage and were not physiologically ready for grazing during the spring lactation production period in May and grazing during this time will severely degrade the grassland ecosystem. Native rangeland forage during the spring has a crude protein content of around 16.3% because of the regreened portions of carryover leaves and the early growth of some new leaves. Spring native rangeland forage had low pasture rent value or production costs of $8.76 per acre, high forage dry matter cost of $89.85 per ton, and moderate crude protein cost of $0.28 per pound. A cow grazing during the spring lactation period requires a large land area of 4.31 acres (4.69 acres per month) at a high forage cost of $37.76 per production period. No supplementation was needed during this period. Total forage feed costs are high at $37.76 per period and $1.35 per day. Calf weight gain was 1.50 lbs per day; accumulated weight gain was 42.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $42.00 per calf. The net return after pasture forage costs was a very low at $4.24 per cow-calf pair and extremely low at $0.98 per acre. The high cost of calf weight gain was $0.90 per pound. The future economic value lost as a result from the ecosystem damage will be much greater than the small return received.

Summer Lactation

Native rangeland managed as a repeated seasonal pasture was evaluated during the summer lactation production period for 135 days (table 3). Native rangeland forage during mid summer has a crude protein content of around 9.6%. Summer native rangeland forage had low pasture rent value or production costs of $8.76 per acre, moderate forage dry matter cost of $48.26 per ton, and acceptable crude protein cost of $0.25 per pound. A cow grazing during the summer lactation period requires a large land area of 11.16 acres (2.52 acres per month) at a forage cost of $97.76 per production period. No supplementation was needed during this period. Total forage feed costs are $97.76 per period and $0.72 per day. Calf weight gain was 1.80 lbs per day; accumulated weight gain was 243.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $243.00 per calf. The net return after pasture forage costs were moderate at $145.24 per cow-calf pair and $13.00 per acre. The cost of calf weight gain was $0.40 per pound.

Fall Lactation

Native rangeland managed as a repeated seasonal pasture was evaluated during the fall lactation production period for 30 days (table 3). Native rangeland forage during the fall has a crude protein content of around 4.8%. Fall native rangeland forage had low pasture rent value or production costs of $8.76 per acre, high forage dry matter cost of $88.85 per ton, and high crude protein cost of $0.92 per pound. A cow grazing during the fall lactation period requires a large land area of 4.52 acres at a forage cost of $39.60 per production period. The crude protein content of mature native rangeland forage is below the requirements of a lactating cow during the fall and would need to be supplemented at 1.21 lbs per cow per day at a cost of $10.89 per period. Total forage feed costs are high at $50.49 per period and $1.68 per day. Calf weight gain was 0.59 lbs per day; accumulated weight gain was 17.70 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $17.70 per calf. The net return after pasture forage costs were a high loss of $32.79 per cow-calf pair and a loss of $7.25 per acre. The extremely high cost of calf weight gain was $2.85 per pound.

12-month season

Native rangeland managed as a repeated seasonal pasture system was evaluated during the 12 months of cow production periods for 365 days (table 3). Native rangeland forage had a low average crude protein content of around 8.6%. Native rangeland forage had low pasture rent value of $8.76 per acre, high forage dry matter average cost of $97.55 per ton, and high crude protein average cost of $0.75 per pound. A cow grazing native rangeland for 12 months requires a large land area of 55.58 acres at a pasture forage cost of $486.89 per year. Crude protein was below the requirements of a cow during 273 days (75% of a year) and was supplemented during 157 days (43% of a year) at a cost of $39.04. Total forage feed costs were extremely high at $525.93 per year and $1.44 per day. Calf average weight gain was 1.24 lbs per day; annual accumulated weight gain was 453.70 lbs. When calf accumulated weight was assumed to have a low value of $1.00 per pound, the gross return was $453.70 per calf. The net return after pasture forage costs were a high loss of $72.23 per cow-calf pair and a loss of $1.30 per acre. The high cost of calf weight gain was $1.16 per pound.

The cows and calves did survive. There were no death losses from severe weather conditions nor malnutrition, however, the cows were light weight but not emaciated and the calves were small and had gained weight at much less than their genetic potentials with the average at 454 lbs. The cows did not receive enough nutrients to fully recover from parturition (birth) and to produce milk at peak potential. The study did not have access to the cooperator's records of the number of open cows each year, which was assumed to be at least a few.

This 12 month no hay management practice is not profitable with a loss of $72 per cow-calf pair and a loss of $1.30 per acre. The only production period that showed a profit was during the summer lactation period for 135 days from 1 June to 14 October. The forage feed cost was $97.76 per period and $0.72 per day. The net return was $145.24 per cow-calf pair and $13.00 per acre. The cost of calf weight gain was $0.40 per pound.

During the other five production periods, the mean cost of pasture forage was $107.40/ton, and pasture crude protein was $0.85/pound. The land area of 44.42 acres cost $389.13 and supplemented crude protein cost $39.04. The average stocking rate was 5.58 acres/month. The total forage feed cost was $428.17 for 230 days (7.5 months) ($1.86/day), and the value of calf accumulated weight was $210.70. Net return was a loss of $217.47 per cow-calf pair and a loss of $4.90 per acre. The cost of calf weight gain was $2.03 per pound.

The reason the net returns are negative is that the available grazable pasture forage was an average of only 168.8 lbs/ac containing only 13.7 lbs/ac of crude protein requiring a large land area per cow-calf pair causing the costs of forage per ton and crude protein per pound to be so great. The low calf weight gain per day was not great enough to pay for the high forage feed and crude protein costs.

The low cash cost per acre for late season native rangeland pasture forage does not translate into low forage feed costs. Cowboy math does not identify low cost forage feed practices. Evaluation of forage dry matter cost/ton, crude protein yield per acre and cost per pound, forage feed cost/day, calf weight gain cost/pound, land area per cow-calf pair, and net return/acre need serious scrutiny in order to evaluate and identify low cost forage feed practices.

A study on the effect of grazing management treatments on residuum vegetation cover was conducted in the badlands of western North Dakota with two years of the study including winter grazing treatments. Each pasture in the study was replicated two times. Grazed residuum herbage biomass was collected by the standard clipping method (Cook and Stubbendieck 1986). Clipped herbage material was collected each growing season month with five quarter meter quadrats (frames) every sample date at each replicated site. Residuum vegetation basal cover was determined by the ten-pin point frame method (Cook and Stubbendieck 1986) with 2000 points collected along transect lines at each replicated site during peak vegetation growth.

The live residuum herbage biomass on the winter grazed treatment consisted of 84.6% native grass, 74.3% cool season grass, 10.4% warm season grass, 6.0% upland sedge, and 9.4% forbs (table 4). The live residuum herbage biomass on the seasonlong practice consisted of 89.9% native grass, 38.9% cool season grass, 51.0% warm season grass, 2.7% upland sedge, and 7.4% forbs (table 4). The live residuum herbage biomass on the twice-over system consisted of 89.8% native grass, 76.8% cool season grass, 13.0% warm season grass, 2.5% upland sedge, and 7.7% forbs (table 4). Winter grazing resulted in 14.8% lower native grass and 9.4% lower total live residum herbage biomass than that on the seasonlong practice and winter grazing resulted in 38.5% lower native grass and 34.8% lower total live residuum herbage biomass than that on the twice-over system.

The live residuum basal cover on the winter grazed treatment consisted of 69.7% native grass, 46.9% cool season grass, 22.7% warm season grass, 13.1% upland sedge, and 17.2% forbs (table 5). The live residuum basal cover on the seasonlong practice consisted of 78.3% native grass, 32.7% cool season grass, 45.6% warm season grass, 5.7% upland sedge, and 16.0% forbs (table 5). The live residuum basal cover on the twice-over system consisted of 76.2% native grass, 56.0% cool season grass, 20.2% warm season grass, 5.3% upland sedge, and 18.5% forbs (table 5). Winter grazing resulted in 40.0% lower native grass and 32.6% lower total live residuum basal cover than that on the seasonlong practice and winter grazing resulted in 43.2% lower native grass and 37.9% lower total live residuum basal cover than that on the twice-over system. Winter grazing also resulted in 82.9% greater bare soil than that on the seasonlong practice and 412.0% greater bare soil than that on the twice-over system.

The residuum vegetation structure resulting from the three grazing management treatments were quite different, with the winter grazed practice composed of the lowest herbage biomass (554.99 lbs/ac), the lowest basal cover (16.5%), and the greatest % bare soil (8.1%), with the seasonlong practice composed of about mean herbage biomass (612.77 lbs/ac), basal cover (24.5%), and % bare soil (4.5%), and with the twice-over system composed of the greatest herbage biomass (850.72 lbs/ac) and basal cover (26.6%) and the lowest % bare soil (1.6%) (tables 4 and 5).

Winter grazing removes a high percentage of carryover leaves of the vegetative tillers that would have produced large quantities of carbohydrates needed to develop new leaves the next growing season. And because the internal grass growth mechanisms and the ecosystem biogeochemical processes are not activated from partial defoliation by grazing animals during the period between the three and a half new leaf stage and the flower stage, the surviving grass tillers produce low numbers of vegetative tillers and reduced leaf biomass sending the ecosystem into spiralling degradation. The lost ecosystem productivity has far greater value than any perceived benefits derived from winter grazing native rangeland.

Table 1. Intake nutrient requirements (lb/d) and difference (%) between old style 1000 lb range cow and modern average production 1200 lb range cow and modern high production 1200 lb range cow.

Nutrient (lb/d) Difference (%)	Dry Gestation	Third Trimester	Early Lactation	Spring Lactation	Summer Lactation	Fall Lactation
Old Style 1000 lb range cow with 12 to 6 lb/d milk production (lb/d)						
Dry matter	21.0	21.0	21.6	22.3	22.3	22.3
Energy (TDN)	9.64	10.98	12.05	11.98	11.98	11.98
Crude Protein	1.30	1.64	1.88	1.78	1.78	1.78
Modern 1200 lb range cow with 20 lb/d average milk production (lb/d)						
Dry matter	24.0	24.0	27.0	27.0	27.0	27.0
Energy (TDN)	11.02	12.62	15.85	15.23	15.23	15.23
Crude Protein	1.49	1.87	2.73	2.51	2.51	2.51
Percent increase in nutrient requirements for average production 1200 lb cow (%)						
Dry matter	14.29	14.29	25.00	21.08	21.08	21.08
Energy (TDN)	14.32	14.94	31.54	27.13	27.13	27.13
Crude Protein	14.62	14.02	45.21	41.01	41.01	41.01
Modern 1200 lb range cow with 30 lb/d high milk production (lb/d)						
Dry matter	24.1	24.2	29.2	29.08	29.08	29.08
Energy (TDN)	11.07	12.73	18.0	17.17	17.17	17.17
Crude Protein	1.50	1.90	3.36	3.06	3.06	3.06
Percent increase in nutrient requirements for high production 1200 lb cow (%)						
Dry matter	14.76	15.24	35.19	30.40	30.40	30.40
Energy (TDN)	14.83	15.94	49.38	43.32	43.32	43.32
Crude Protein	15.38	15.85	78.72	71.91	71.91	71.91

Data from Manske 2014a.

Table 2. Availability of sufficient crude protein for range cows on 12-month pasture forage management strategies.

12-month Management Strategies	Forage with Adequate Crude Protein		Forage Deficient in Crude Protein		Crude Protein Supplementation Provided		Crude Protein Supplementation Not Provided	
	Days	% of 12-mo	Days	% of 12-mo	Days	% of 12-mo	Days	% of 12-mo
Deferred Grazing	67	18%	298	82%	135	37%	163	45%
6.0-m Seasonlong	77	21%	288	79%	182	50%	106	29%
Repeated Seasonal	92	25%	273	75%	152	42%	121	33%
4.5-m Seasonlong	214	59%	151	41%	45	12%	106	29%
Twice-over Rotation	350	96%	15	4%	0	0%	15	4%

Data from Manske 2014b.

Table 3. Costs and returns for native rangeland, without hay, during cow production periods with 1200 lb cow and calf born in mid March.

Costs/Returns		37 Day Dry Gestation	90 Day Third Trimester	45 Day Early Lactation	28 Day Spring Lactation	135 Day Summer Lactation	30 Day Fall Lactation	12 Month Season
Forage DM Wt	lbs/ac	180.0	145.0	125.0	195.0	363.0	199.0	197.0
Production Costs	$/ac	8.76	8.76	8.76	8.76	8.76	8.76	8.76
Forage DM Costs	$/ton	97.33	120.83	140.16	89.85	48.26	88.85	97.55
Crude Protein	%	4.8	4.8	9.2	16.3	9.6	4.8	8.6
CP Yield	lb/ac	8.6	7.0	11.5	31.8	34.8	9.6	16.9
CP Costs	$/lb	1.01	1.26	0.76	0.28	0.25	0.92	0.75
Forage/day	lbs/d	30	30	30	30	30	30	30
Land Area	ac	6.17	18.62	10.80	4.31	11.16	4.52	55.58
CP supp./day	lbs/d	1.49	0.43	-	-	-	1.21	0.83
Forage Costs	$/pp	54.05	163.11	94.61	37.76	97.76	39.60	486.89
CP supp. Costs	$/pp	16.54	11.61	-	-	-	10.89	39.04
Total Feed Costs	$/pp	70.59	174.72	94.61	37.76	97.76	50.49	525.93
Cost/day	$/d	1.91	1.94	2.10	1.35	0.72	1.68	1.44
Calf Wt Gain	lbs/pp	27.00	68.00	56.00	42.00	243.00	17.70	453.70
Wt. Value @$1.00/lb	$	27.00	68.00	56.00	42.00	243.00	17.70	453.70
Net Return/C-C pr	$	-43.59	-106.72	-38.61	4.24	145.24	-32.79	-72.23
Net Return/Acre	$	-7.07	-5.73	-3.58	0.98	13.00	-7.25	-1.30
Calf Gain Cost	$/lb	2.61	2.57	1.69	0.90	0.40	2.85	1.16

Table 4. Mean growing season herbage biomass (lbs/ac) by biotype categories on the silty ecological sites on three grazed management strategies located in the badlands of western North Dakota, 1993-1994.

Silty Site	Winter Grazed	Seasonlong Grazed	Twice-over Grazed
Cool Season	412.07	238.26	653.50
Warm Season	57.47	312.67	110.39
Upland Sedge	33.23	16.62	21.42
Forbs	52.22	45.23	65.40
Grasses	469.54	550.93	763.89
Graminoids	502.77	567.55	785.31
Total Live	554.99	612.77	850.72

Table 5. Mean growing season basal cover (%) by biotype categories on the silty ecological sites on three grazed management strategies located in the badlands of western North Dakota, 1993-1994.

Silty Site	Winter Grazed	Seasonlong Grazed	Twice-over Grazed
Cool Season	7.76	8.01	14.91
Warm Season	3.76	11.18	5.38
Upland Sedge	2.16	1.39	1.40
Forbs	2.85	3.93	4.93
Grasses	11.52	19.19	20.29
Graminoids	13.68	20.58	21.69
Total Live	16.53	24.51	26.62
Bare Soil	8.14	4.45	1.59

Practical harvested forage techniques

Some producers do provide low cost harvested hay to their cows. Most of this hay is putup late when the forage dry matter yields larger bales per acre, however, the late season forage is usually low in crude protein and energy (TDN), therefore, crude protein and energy (TDN) will need to be supplemental at additional costs. Cutting perennial grass hay between the boot stage and the flower stage, and cutting annual cereal hay between the boot stage and the early milk stage, yields forages with adequate quantities of crude protein and energy (TDN) with no additional cost. The quantity of dry matter would be reduced with little consequence because it has no economic value to livestock production.

Forage dry matter does not have a real economic value because it is not incorporated into the beef weight produced. All of the dry matter consumed by beef cattle is nondigestible and is deposited on the ground as manure in a couple of days. The dry matter component of forage is simply the carrier of the nutrients it contains; therefore, the cost of the forage dry matter is only indirectly related to forage feed costs. The nutrients (major and minor essential elements) are the valuable renewable products produced by forage plants on the land natural resources. The cow processes the forage nutrients and produces milk resulting in calf weight accumulation. This calf weight is the commodity sold at the market, nevertheless, the original source of the income from the sale of beef weight is the forage nutrients. These renewable forage nutrients are the primary unit of production in a cow-calf beef operation, and they are the source of new wealth from agricultural use of grazingland and hayland resources.

Forage nutrients are comprised of essential elements. The essential elements are required for life to exist by ensuring growth and development of organisms and the maintenance of all life functions. Livestock require 21 elements (table 6). Very large amounts of four major essential elements are required: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). Small amounts of seven macrominerals are required: calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), sodium (Na), and chlorine (Cl). Very small amounts of ten microminerals are required: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), iodine (I), cobalt (Co), selenium (Se), molybdenum (Mo), chromium (Cr), and nickel (Ni). The required quantity of each essential element varies with the cow's production period, body weight, quantity of milk production, and genetic production potential (Manske 2001).

The major forage produced nutrients are energy (TDN) and crude protein. The energy (TDN) produced by forage plants is part of the ecosystem's carbon cycle. Plants capture and fix carbon from atmospheric carbon dioxide with the hydrogen from soil water during the process of photosynthesis which converts energy from the sun into chemical energy. The assimilated carbon is combined in several ways to form various types of sugars and starches that are collectively called carbohydrates (CHO). These carbohydrates can be used as an energy source by the plant or by the herbivore that consumes plant parts. Capturing energy by fixing carbon has a relatively low impact on organisms that possess chlorophyll and on the ecosystem resources.

Feeder beef animals grow rapidly when fed a high energy grain based ration, however, these animals are never asked to go back to a forage based ration. Because of this phenomenon, some beef producers supplement energy to their cow herd in order to improve cow performance on their low cost poor quality forages. Supplements high in energy from nonstructural carbohydrates (NSC) (starches and sugars) causes the ruminal pH to decrease, which reduces growth of fibrolytic bacteria. Low quantities of fibrolytic bacteria result in reduced forage intake, and low forage fiber digestibility (Kunkle et al. 1999, Baublits et al. 2003, Hales et al. 2007). When these cows go back to a forage based ration or to grass pasture, they do not have adequate quantities of fibrolytic bacteria to digest the forage fibers causing a high amount of the nutrients contained in the forage to not be captured in the rumen and thus being lost to the animals. Supplemented energy as nonstructural carbohydrates (NSC) from products containing high amounts of grains or molasses should not be given to the cows that are intended to remain productive in the herd for many years.

Energy supplements that can be fed to a cow herd that have low impact on forage intake and forage digestibility have low nonstructural carbohydrates at less than 30% NSC and still have high total digestible nutrients (TDN) at greater than 75% TDN are the many fibrous coproduct feed stuffs. These include, but are not limited to, soybeans hulls, wheat middlings, corn gluten feed, beet pulp, distillers grains, and brewers grains.

Crude protein becomes deficient in beef cattle forage based rations at earlier forage plant growth stages than does energy. The crude protein produced by forage plants is part of the ecosystem's nitrogen cycle. Inorganic nitrogen is taken up by plant roots from the surrounding rhizosphere microorganisms and, through complex processes, the plant combines the inorganic nitrogen with carbon, hydrogen, and oxygen to synthesize different kinds of amino acids. The amino acids can be used immediately to build complex nitrogenous compounds, or the amino acids can float around inside the plant for later use. Amino acids are building blocks for proteins, nucleotides, and chlorophyll. Proteins are used to form enzymes, hormones, and structural components of cells. Nucleotides build nucleic acids, deoxyribonuclic acid (DNA) and ribonucleic acid (RNA), that are the genetic material that control all cellular functions and heredity (Coyne et al. 1995). About half of the organic nitrogen is in the form of amino compounds (Brady 1974). The large nitrogenous compounds that have been consumed by herbivores and deposited as excreta and the dead plant material are broken down and converted from organic nitrogen into inorganic nitrogen through numerous complex stages by soil microorganisms in the rhizosphere. Transforming nitrogen from inorganic nitrogen to organic nitrogen and back to inorganic nitrogen is complex and has a great impact on many organisms at multiple trophic levels and on the ecosystem resources. A pound of crude protein has a greater impact on the natural resources of an ecosystem to produce and a greater influence on the cost of livestock forage feed than the production of a pound of energy (TDN).

The quantity of crude protein captured per acre as livestock feed is the factor that has the greatest influence on the cost of pasture forage and harvested forage and on the amount of new wealth generated from the land resources. The weight of crude protein captured per acre is related to the percent crude protein content and the weight of the forage dry matter at the time of grazing or haying. The cost per pound of crude protein is determined by the weight of the crude protein captured per acre prorated against the forage production costs which include the land costs, equipment costs, and labor costs per acre. Reduction in livestock feed costs results from capturing greater quantities of crude protein per acre. Capturing greater quantities of the produced crude protein from a land base causes a reduction in the amount of land area required to feed a cow-calf pair and results in lowering the forage feed costs because the forage production costs per acre are spread over a greater number of pounds of crude protein. The greater quantity of pounds of calf weight gain per acre increases the quantity of new wealth generated per acre of land resources.

The greatest quantity of crude protein and energy (TDN) per acre available to animals with ruminant digestive systems are in the green leaves at the flower stage of perennial and annual grasses and at the full flower stage of legumes. When the seeds fill, nutrient material is moved from the leaves to the seed heads or pods. During the transfer process, half of the material is lost or used and only half reaches the seeds. For example, a field of annual cereal will yield double the weight of crude protein per acre when cut for hay at the flower stage than when harvested for grain at the mature stage.

Perennial and annual grass forages that are grazed or hayed at a mature plant stage, after flowering, are generally high-cost forages. The quantity of dry matter per acre is greater, and the size of the bales per acre are larger, causing a reduction in production costs per ton of forage dry matter. However, the quantity of crude protein per acre is lower causing an increase in cost per pound of crude protein and requiring greater land area to provide adequate feed for a cow-calf pair resulting in an increase in forage feed costs and reducing the pounds of calf weight gain per acre reducing the quantity of captured wealth per acre.

Perennial grass forages that are grazed at an early plant stage, after the three and a half new leaf stage and before the flower stage are low cost forage. Perennial grass and annual cereal forage that are cut for hay early between the boot stage and the early milk stage are low cost forages. The quantity of forage dry matter per acre is less causing an increase in production costs per ton of forage dry matter but the quantity of crude protein captured per acre is greater causing a decrease in cost per pound of crude protein and requiring less land area to provide adequate feed for a cow-calf pair resulting in a decrease of forage feed costs and an increase in the quantity of captured wealth.

Legume forages are different than grass forages and yield the greatest weight of crude protein per acre when the plants are at full growth stage but before the pods start to fill and the leaves start drying from senescence. The cost per pound of crude protein is lower for legume forages when plants are cut one time per year during a late full-growth stage resulting in lower forage feed costs and in greater captured wealth. Legume forages cut at early plant growth stages yield higher percentage of crude protein but because of the lower weight of crude protein per acre, the cost per pound of crude protein is higher and the forage feed costs are higher.

Harvested forage types containing 18% crude protein or greater are generally high-cost forages and have been removed from consideration as forage feed for beef cows during this study because the cost for the large quantity of supplemental roughage needed to balance the ration greatly reduces the amount of net returns per cow-calf pair and per acre.

Advanced Harvested Forage Technology

This report is the synthesis of 25 years of research to identify the factors that affect harvested forage costs for beef cows on the Northern Mixed Grass Prairie and to determine which factors can be controlled by management to improve profit margins from beef cow-calf production and to increase the new wealth generated from the land renewable natural resources without depletion of future production. Harvested forage management strategies will be evaluated for low forage feed costs and high net returns per acre for each of the six range cow production periods.

Evaluation of the production costs of livestock forage management practices is complicated because the various pasture forage types and harvested forage types have complex differences. Traditional livestock practices assume the source of income to be from the sale of animal weight. Pasture forage and harvested forage, and labor and equipment are considered to be costs of production. Profits result when the sale value of livestock weight is greater than the paid production costs. Under this traditional concept, reduction of livestock production costs require reduction of the labor and equipment costs and the pasture forage and harvested forage costs usually resulting in cow and calf weight performance to be well below their genetic potential.

This traditional paradigm that the wealth comes from the sale of livestock weight causes major problems to provide forage with adequate nutrients to modern beef cows. Grazing native range pastures after mid October has low cash output per acre. However, cost per ton of forage and cost per pound of crude protein are outrageously high because of low forage quantity and low crude protein content per acre (table 3). Late cut grass hay has low cash cost per ton but the cost per pound of crude protein is very high. Modern equipment used for beef production are intended to reduce labor, however, these equipment costs can be greatly reduced to a hand scythe and pitch fork, but then the labor costs become a problem and an additional skilled staff is needed just to feed the workers. The modern equipment is needed, however, the expenditures should remain conservative. Lets change this old paradigm to the source of wealth originates from the renewable forage nutrients produced on the land natural resources.

Actually, reductions in forage dry matter costs, forage production costs, seed costs, land rent costs, equipment operation and depreciation costs, and labor costs all influence livestock feed costs and may cause some reduction in cash expenditures; unfortunately, reductions in these costs do not directly regulate livestock forage feed costs because these costs do not respond proportionally to the variations in quantities of forage needed to provide livestock with adequate amounts of nutrients resulting from the differences in the weight of crude protein captured per acre through the grazing or haying of various forage types at different plant growth stages.

Production of the beef cow herd is the last sector of the meat industry that continues to evaluate feed costs and to make feed management decisions from the cost per unit of dry matter. The swine, poultry, and dairy industries and the feeder sector of the beef industry have switched to efficient feed management systems that evaluate feed costs from the cost per unit of the nutrients.

Traditional evaluation of costs for forage management practices used the criteria of forage dry matter costs, forage production costs, land rent costs, equipment costs, and labor costs which do not identify forage types that provide low forage feed costs because these factors do not fluctuate with forage quality and thus do not directly regulate forage feed costs and have no diagnostic value.

The three most important factors that have diagnostic value in identification of forage management practices with low forage feed costs are the quantitative values of cost per pound of captured crude protein, cost per day of forage feed, and cost per pound of calf weight gain. The two important factors that have diagnostic value in identification of forage management practices that efficiently capture greater new wealth generated from the land renewable natural resources are the quantitative values of size of land area per cow-calf pair (which affects pounds of calf gain per acre) and net returns after feed costs per acre.

Procedure

The quantifiable factors that should be included in evaluations of forage types are harvested forage dry matter weight per acre, production cost per acre including land rent cost, equipment cost, labor cost, and seed cost; percent crude protein, captured crude protein weight per acre, crude protein cost per pound, cow size, forage allocation per day, land area per cow-calf pair, supplemental roughage cost, total forage feed cost, forage feed cost per day, calf weight gain performance, low market value of calf weight, returns after feed cost per cow-calf pair, returns after feed cost per acre, and calf weight gain cost per pound.

Production cost per acre was determined by adding land rent per acre, custom farm work cost per acre, seed cost per acre, and baling cost at per half ton rate.

Cost per ton of forage dry matter (DM) was determined by dividing production costs per acre by pounds of forage dry matter yield per acre and multiplying the quotient by 2000 pounds.

Cost per pound of crude protein (CP) was determined from the pounds of forage dry matter per acre multiplied by percentage of crude protein to derive pounds of captured crude protein per acre; then production cost per acre was divided by pounds of captured crude protein per acre.

Cow weight of 1200 lbs, average potential milk production, calf born in mid March, and cow production period on table 7 determined pounds of daily crude protein requirement.

Pounds of forage dry matter to provide as feed per cow-calf pair per day was determined from the pounds of crude protein required per cow per day during the production period divided by the percent crude protein of the forage type. Pounds of forage dry matter per day was multiplied by the number of days per production period to determine total weight of forage per period. The production cost per acre was divided by the forage dry matter yield per acre to determine cost per pound of forage dry matter. Forage cost per production period was determined by the total pounds of forage feed per period multiplied by the forage cost per pound.

Pounds of supplemental roughage to provide per cow-calf pair per day was determined from the total dry matter allocation per day from table 7 or 8 and subtracting the pounds of forage to provide per day. The source of roughage was year old crested wheatgrass hay valued at $35 per ton or $0.0175/lb and was considered to contain no available nutrients. Roughage cost was determined from the pounds of roughage provided per day multiplied by the number of day per production period and then multiplied by the roughage cost per pound ($0.0175).

Pounds of supplemental crude protein to provide was not determined for harvested forage types because any forage types that were low in crude protein for a cow production period were not used as forage feed during that production period. The source of wealth generated from the land resources depends on the quantity of crude protein captured per acre. A forage type low in crude protein generates low wealth from the land and thus not considered for use as forage feed.

Total feed cost per production period were determined by the sum of the harvested forage cost and the supplemented roughage cost per production period. The total feed cost per production period was divided by the number of days to determine the total feed cost per day.

Dollar value of calf accumulated weight gain per production period was determined by multiplying an assumed low market value of $1.00 per pound. A low market value was used to evaluate and identify harvested forage types that would produce positive returns after feed costs during low portions of the cattle cycle. Calf fetus weight gain was estimated to be 0.68 lbs/day during the dry gestation and to be 0.78 lbs/day during the third trimester production periods, based on an average birth weight of 95 pounds. Live calf accumulated weight gain was determined by subtracting calf live weight at the beginning of the growth period from calf live weight at the end of the growth period. The accumulated calf weight gains determined for the selected harvested forage types were averaged for each production period because the rations for the harvested forage types were designed to provide the same required quantity of crude protein during each production period and these forage types were evaluated over several years with only a few types analyzed each year.

Net return after feed costs per cow-calf pair was determined by subtracting the total feed cost per production period from the dollar value of the accumulated calf weight gain per production period. Net return after feed cost per acre was determined by dividing the net return per cow-calf pair by the number of acres of land area needed to feed a cow-calf pair per production period.

Cost per pound of calf weight gain per production period was determined by dividing the total feed cost per period by the pounds of calf weight accumulated per period.

This study evaluates four common harvested forage types with swathing occurring at two different plant growth stages. Perennial crested wheatgrass hay was cut early during the boot stage, and was cut late at the mature stage. Annual late maturing type oat forage hay was cut early at the beginning of the milk stage and was cut late at the hard dough stage. Annual forage barley hay was cut early at the beginning of the milk stage, and was cut late at the hard dough stage. Annual field pea forage hay was cut late at the full growth stage before pods started to fill. Annual field pea hay was also cut early, however, this hay was not included in the study because forage dry matter yield/ac was 66% lower than that for late cut pea forage, the crude protein content was greater than 18% with a 30% lower yield/ac than that for late cut pea forage, the forage feed ration had a high roughage cost with 28.6% more roughage than pea forage, the total feed cost was relatively high, and the returns/ac were the lowest of the annual forage feeds.

The mean forage dry matter yield per acre and percent crude protein for annual forage crop varieties cut for hay were taken from a five year agronomic forage crop study at the Dickinson Research Extension Center conducted and reported by Carr (1995-1999). Data for pasture forage types used during the spring, summer, and fall production periods were from Manske (2018b).

North Dakota State University agronomists at the Carrington, Dickinson, Hettinger, Minot, and Williston Research Extension Center (REC) conducted investigations on alternative use of cropland for the production of annual forages that can be used as harvested hay or silage during 1994 to 1999. Beef producers should consult the annual forage production reports from the REC nearest their locations for adapted varieties, forage dry matter yield per acre, and percent crude protein data to assist in selection of annual harvested forage types suitable for their operation.

The nutrient requirements for a 1200 lb range cow with a calf born in mid March and with average milk production was met each day during six cow production periods in accordance with recommendations from NRC 1996 (table 7). During the spring, summer, and fall lactation production periods, dry matter forage allocation followed pasture grazing quantities (table 8). The daily minor essential element requirements for a 1200 lb cow with average milk production are reported for macrominerals (lbs/day) and microminerals (g/day) on table 9. Research data has not determined the daily requirements for one macromineral and three microminerals nor ascertained evidence of deficiencies under practical conditions. The nutrient requirements and forage allocation will be described separately for each cow production period.

Table 6. Essential Elements Required by Animals.

Essential Nutrients

Crude Protein, Energy, Water, Vitamins

Major Essential Elements

Carbon (C), Hydrogen (H), Nitrogen (N), and Oxygen (O).

Minor Essential Elements

- Macrominerals

  Calcium (Ca), Phosphorus (P), Potassium (K),
  Magnesium (Mg), Sulfur (S), Sodium (Na), Chlorine (Cl)

- Microminerals

  Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu),
  Iodine (I), Cobalt (Co), Selenium (Se),
  Molybdenum (Mo), Chromium (Cr), Nickel (Ni)

Table 7. Intake nutrient requirements (lb/d) for modern range cows with average milk production during cow production periods.

Nutrient (lb/d)	Dry Gestation	Third Trimester	Early Lactation	Spring Lactation	Summer Lactation	Fall Lactation
1000 lb cows						
Dry matter	21	21	24	24	24	24
Energy (TDN)	9.64	10.98	14.30	13.73	13.73	13.73
Crude Protein	1.30	1.64	2.52	2.30	2.30	2.30
Calcium	0.03	0.05	0.07	0.06	0.06	0.06
Phosphorus	0.02	0.03	0.05	0.04	0.04	0.04
1200 lb cows						
Dry matter	24	24	27	27	27	27
Energy (TDN)	11.02	12.62	15.85	15.23	15.23	15.23
Crude Protein	1.49	1.87	2.73	2.51	2.51	2.51
Calcium	0.04	0.06	0.08	0.07	0.07	0.07
Phosphorus	0.03	0.04	0.05	0.05	0.05	0.05
1400 lb cows						
Dry matter	27	27	30	30	30	30
Energy (TDN)	12.42	14.28	17.40	16.71	16.71	16.71
Crude Protein	1.67	2.13	2.94	2.70	2.70	2.70
Calcium	0.04	0.07	0.08	0.08	0.08	0.08
Phosphorus	0.03	0.05	0.06	0.05	0.05	0.05

Data from NRC 1996.

Table 8. Daily dry matter allocation (lb/d) for modern range cows grazing pasture forage.

DM lb/d	1000 lb cow	1200 lb cow	1400 lb cow
Dry matter allocation	26	30	33

Date from Manske 2012.

Table 9. Daily minor essential element requirements of macrominerals (lbs/day) and microminerals (g/day) during six production periods for 1200 lb beef cows with average milk production.

Minor Essential Elements	Dry Gestation	Third Trimester	Early Lactation	Spring Lactation	Summer Lactation	Fall Lactation
Macrominerals (lbs/day)						
Calcium	0.04	0.06	0.08	0.07	0.07	0.07
Phosphorous	0.03	0.04	0.05	0.05	0.05	0.05
Potassium	0.14	0.14	0.19	0.19	0.19	0.19
Magnesium	0.03	0.03	0.05	0.045	0.045	0.045
Sulfur	0.04	0.04	0.04	0.04	0.04	0.04
Sodium	0.01	0.02	0.03	0.03	0.03	0.03
Chlorine	-	-	-	-	-	-
Microminerals (g/day)						
Iron	0.5443	0.5443	0.6124	0.6124	0.6124	0.6124
Manganese	0.4355	0.4355	0.4899	0.4899	0.4899	0.4899
Zinc	0.3266	0.3266	0.3674	0.3674	0.3674	0.3674
Copper	0.1089	0.1089	0.1225	0.1225	0.1225	0.1225
Iodine	0.0054	0.0054	0.0061	0.0061	0.0061	0.0061
Cobalt	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012
Selenium	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012
Molybdenum	-	-	-	-	-	-
Chromium	-	-	-	-	-	-
Nickel	-	-	-	-	-	-

Data from NRC 1996.

Results

Forage feed cost is affected by the quantity of forage dry matter harvested per acre, the production cost per acre, the forage dry matter cost per ton, the percent crude protein, the crude protein yield in pounds per acre, and the crude protein cost per pound. Four common forage types were included in this study, three forage types were cut at two different growth stages and one forage type was cut at one growth stage.

The early and late cut perennial crested wheatgrass hays had significantly lower forage yield per acre than the five annual forage types. The forage yield per acre for the five annual forage types were not significantly different. The late cut crested wheatgrass hay yielded 300 pounds per acre greater forage dry matter than the early cut crested wheatgrass hay. The production cost per acre for the early and late cut crested wheatgrass were significantly lower than those for the five annual forage types. The production cost per acre for the late pea forage hay was significantly greater than those for the other harvested types. The forage dry matter cost per ton was significantly lower for the late oat forage hay and was significantly greater for the early crested wheatgrass hay.

The percent crude protein was significantly higher for the early crested wheatgrass hay and the late pea forage hay and was significantly lower for the late crested wheatgrass hay. The crude protein yield in pounds per acre was significantly greater for the late pea forage hay and was significantly lower for the late crested wheatgrass hay. The cost per pound of captured crude protein was significantly greater for the late crested wheatgrass hay and was not significantly different for the other harvested types.

Net return per cow-calf pair is affected by the quantity of calf weight gain during a production period related to the total forage feed cost during that period. Net return per cow-calf pair increases when the cow has adequate quality of forage to milk at the genetic potential permitting the calf to grow at the genetic potential. Net return per acre is affected by the land area size used to produce the amount of forage with adequate quantities of crude protein required by a cow-calf pair during a production period. Net return per acre increases when the land area per cow-calf pair decreases.

Dry Gestation

The dry gestation production period was 37 days during late fall from 13 November to 20 December. The dry gestation period has the lowest nutrient requirements because there is no nursing calf or milk production and the developing fetus is small during middle gestation and does not have high nutrient demands. Heavy cows can lose weight during this period without detrimental future effects on reproduction and production performance. Cows with moderate body condition should maintain body weight because the cost to replace lost pounds is greater during other production periods. Thin cows should gain weight during this period because each pound gained requires less feed and costs less than weight gained during other production periods. During the 37 days dry gestation period, a 1200 lb cow requires 888 lbs of forage dry matter, 407.74 lbs of energy (TDN), and 55.13 lbs of crude protein, with daily intake of 24 lbs dry matter, 1.49 lbs crude protein (table 7), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 10.3 lbs/day to provide 1.5 lbs CP/day, with 13.7 lbs/day of roughage added to the ration. Production of 381.10 lbs of early cut crested wheatgrass hay would require 0.29 acres at a cost of $7.77/period, with roughage costs at $8.87/period, the total feed cost was $16.64/period, or $0.45/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were a low of $8.36/cow-calf pair and a moderate gain of $28.83/acre. The high cost of calf fetus weight gain was $0.67/lb.

Late Crested Wheatgrass Hay

Crested wheatgrass hay cut late at the mature stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 6.4%. Late cut crested wheatgrass hay had production costs of $28.11/ac, forage dry matter costs of $34.80/ton, and crude protein costs of

$0.28/lb. Late cut crested wheatgrass hay would be fed at 24.0 lbs/day to provide 1.5 lbs CP/day, with no roughage added. Production of 888 lbs of late cut crested wheatgrass hay would require 0.56 acres at a cost of $15.74/period, with no roughage, the total feed cost was $15.74/period, or $0.43/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were a low of $9.26/cow-calf pair and a low of $16.54/acre. The high cost of calf fetus weight gain was $0.63/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 11.5 lbs/day to provide 1.5 lbs CP/day, with 12.5 lbs/day of roughage added to the ration. Production of 425.50 lbs of early cut forage barley hay would require 0.09 acres at a cost of $6.14/period, with roughage costs at $8.09/period, the total feed cost was $14.23/period, or $0.38/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were a low of $10.77/cow-calf pair and a high gain of $119.67/acre. The cost of calf fetus weight gain was $0.57/lb.

Late Forage Barley Hay

Forage barley hay cut late at the hard dough stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 9.2%. Late cut forage barley had production costs of $70.35/ac, forage dry matter costs of $27.40/ton, and crude protein costs of $0.15/lb. Late cut forage barley hay would be fed at 16.2 lbs/day to provide 1.5 lbs CP/day, with 7.8 lbs/day of roughage added to the ration. Production of 599.40 lbs of late cut forage barley hay would require 0.12 acres at a cost of $8.44/period, with roughage costs at $5.05/period, the total feed cost was $13.49/period, or $0.36/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were $11.51/cow-calf pair and $95.92/acre. The cost of calf fetus weight gain was $0.54/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 13.0 lbs/day to provide 1.5 lbs CP/day, with 11.0 lbs/day of roughage added to the ration. Production of 481.00 lbs of early cut oat forage hay would require 0.10 acres at a cost of $6.92/period, with roughage costs at $7.12/period, the total feed cost was $14.04/period, or $0.38/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were $10.96/cow-calf pair and a high gain of $109.60/acre. The cost of calf fetus weight gain was $0.56/lb.

Late Oat Forage Hay

Oat forage hay cut late at the hard dough stage was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 7.8%. Late cut oat forage hay had production costs of $74.53/ac, forage dry matter costs of $26.40/ton, and crude protein costs of $0.17/lb. Late cut oat forage hay would be fed at 19.1 lbs/day to provide 1.5 lbs CP/day, with 4.9 lbs/day of roughage added to the ration. Production of 706.70 lbs of late cut oat forage hay would require 0.13 acres at a cost of $9.69/period, with roughage costs at $3.17/period, the total feed cost was $12.86/period, or $0.35/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were $12.14/cow-calf pair and $93.38/acre. The cost of calf fetus weight gain was $0.51/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 37 day dry gestation production period (table 10). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $37.40/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 10.3 lbs/day to provide 1.5 lbs CP/day, with 13.7 lbs/day of roughage added to the ration. Production of 381.10 lbs of late cut pea forage hay would require 0.08 acres at a cost of $6.95/period, with roughage costs at $8.87/period, the total feed cost was $15.82/period, or $0.43/day. Calf fetus weight gain was assumed to be 0.68lbs/day and accumulated weight gain was 25.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $25.00 per calf. The net returns after feed costs were $9.18/cow-calf pair and a high gain of $114.75/acre. The cost of calf fetus weight gain was $0.63/lb.

During the dry gestation period the total feed cost was significantly low for the late oat forage hay at $12.86 per period, and $0.35 per day, and was significantly high for the early cut crested wheatgrass hay at $16.64 per period, and $0.45 per day. Net return per cow-calf pair were all very low because the fetal calf weight gain was low, however, these values were all positive; most forage feed types fed during the dry gestation have negative net returns. Net return per acre were not significantly different for the five annual forage types which were all significantly greater than the early and late perennial crested wheatgrass hays.

Table 10. Costs and returns for forage types during 37 day dry gestation production period with 1200 lb cow.

Costs/Returns		Early Crested Wheat Hay	Late Crested Wheat Hay	Early Forage Barley Hay	Late Forage Barley Hay	Early Oat Forage Hay	Late Oat Forage Hay	Late Pea Forage Hay
Forage DM Wt	lbs/ac	1300.0	1600.0	4733.0	5133.0	4667.0	5667.0	4650.0
Production Costs	$/ac	26.50	28.11	68.21	70.35	69.17	74.53	86.87
Forage DM Costs	$/ton	40.80	34.80	28.80	27.40	29.60	26.40	37.40
Crude Protein	%	14.5	6.4	13.0	9.2	11.5	7.8	14.4
CP Yield	lb/ac	189	102	606	468	535	435	685
CP Costs	$/lb	0.14	0.28	0.11	0.15	0.13	0.17	0.13
Forage/day	lbs/d	10.3	24.0	11.5	16.2	13.0	19.1	10.3
Land Area	ac	0.29	0.56	0.09	0.12	0.10	0.13	0.08
Roughage/day	lbs/d	13.7	-	12.5	7.8	11.0	4.9	13.7
Forage Costs	$/pp	7.77	15.74	6.14	8.44	6.92	9.69	6.95
Roughage Costs	$/pp	8.87	-	8.09	5.05	7.12	3.17	8.87
Total Feed Costs	$/pp	16.64	15.74	14.23	13.49	14.04	12.86	15.82
Cost/day	$/d	0.45	0.43	0.38	0.36	0.38	0.35	0.43
Calf Wt Gain	lbs/pp	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Wt. Value @$1.00/lb	$	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Net Return/C-C pr	$	8.36	9.26	10.77	11.51	10.96	12.14	9.18
Net Return/Acre	$	28.83	16.54	119.67	95.92	109.60	93.38	114.75
Calf Gain Cost	$/lb	0.67	0.63	0.57	0.54	0.56	0.51	0.63

Third Trimester

The third trimester production period was 90 days during winter from 20 December to 20 March. The third trimester period has increased nutrient requirements. Although the cow has no calf at her side and is not producing milk, the developing fetus is growing at an increasing rate. The weight gain from the fetus and related fluid and tissue is about one pound per day during the last 2 or 2.5 months when the fetus is growing very rapidly (BCRC 1999). It is important that higher quality forage that meets the nutritional requirements be provided during this period to maintain the weight of cows in moderate to good body condition and to ensure a strong, healthy calf. Feeding forages containing insufficient nutrients during this period causes a reduction in cow body condition and results in delayed estrual activity and a delay in rebreeding. During the 90 day third trimester period, a 1200 lb cow requires 2160 lbs of forage dry matter, 1135.8 lbs of energy (TDN), and 168.3 lbs of crude protein, with daily intake of 24 lbs dry matter, 1.87 lbs crude protein (table 7), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 12.9 lbs/day to provide 1.9 lbs CP/day, with 11.1 lbs/day of roughage added to the ration. Production of 1161.00 lbs of early cut crested wheatgrass hay would require 0.89 acres at a cost of $23.59/period, with roughage costs at $17.48/period, the total feed cost was $41.07/period, or $0.46/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $28.93/cow-calf pair and $35.51/acre. The high cost of calf fetus weight gain was $0.59/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 14.4 lbs/day to provide 1.9 lbs CP/day, with 9.6 lbs/day of roughage added to the ration. Production of 1296.00 lbs of early cut forage barley hay would require 0.27 acres at a cost of $18.42/period, with roughage costs at $15.12/period, the total feed cost was $33.54/period, or $0.37/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $36.46/cow-calf pair and a high gain of $135.04/acre. The cost of calf fetus weight gain was $0.48/lb.

Late Forage Barley Hay

Forage barley hay cut late at the hard dough stage was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 9.2%. Late cut forage barley hay had production costs of $70.35/ac, forage dry matter costs of $27.40/ton, and crude protein costs of $0.15/lb. Late cut forage barley hay would be fed at 20.3 lbs/day to provide 1.9 lbs CP/day, with 3.7 lbs/day of roughage added to the ration. Production of 1827.00 lbs of late cut forage barley hay would require 0.36 acres at a cost of $25.33/period, with roughage costs at $5.83/period, the total feed cost was $31.16/period, or $0.35/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $38.84/cow-calf pair and $107.89/acre. The cost of calf fetus weight gain was $0.45/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 16.3 lbs/day to provide 1.9 lbs CP/day, with 7.7 lbs/day of roughage added to the ration. Production of 1467.00 lbs of early cut oat forage hay would require 0.31 acres at a cost of $21.44/period, with roughage costs at $12.13/period, the total feed cost was $33.57/period, or $0.37/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $36.43/cow-calf pair and a high gain of $117.52/acre. The cost of calf fetus weight gain was $0.48/lb.

Late Oat Forage Hay

Oat forage hay cut late at the hard dough stage was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 7.8%. Late cut oat forage hay had production costs of $74.53/ac, forage dry matter costs of $26.40/ton, and crude protein costs of $0.17/lb. Late cut oat forage hay would be fed at 24.0 lbs/day to provide 1.9 lbs CP/day, with no roughage added. Production of 2160.00 lbs of late cut oat forage hay would require 0.38 acres at a cost of $28.32/period, with no roughage, the total feed cost was $28.32/period, or $0.32/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $41.68/cow-calf pair and a high gain of $109.68/acre. The cost of calf fetus weight gain was $0.41/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 90 day third trimester production period (table 11). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $37.40/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 13.0 lbs/day to provide 1.9 lbs CP/day, with 11.0 lbs/day of roughage added to the ration. Production of 1170.00 lbs of late cut pea forage hay would require 0.25 acres at a cost of $21.72/period, with roughage costs at $17.33/period, the total feed cost was $39.05/period, or $0.43/day. Calf fetus weight gain was assumed to be 0.78lbs/day and accumulated weight gain was 70.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $70.00 per calf. The net returns after feed costs were $30.95/cow-calf pair and a high gain of $123.80/acre. The cost of calf fetus weight gain was $0.56/lb.

During the third trimester period the total feed cost was significantly low for the late oat forage hay at $28.32 per period, and $0.32 per day, and was significantly high for the early crested wheatgrass hay at $41.07 per period, and $0.46 per day. Net return per cow-calf pair was significantly high for the late oat forage hay at $41.68 per period and was significantly low for the early crested wheatgrass hay at $28.93 per period. Net return per acre were significantly high for all the five annual forage types at a mean $118.79 per period and was significantly low for the early crested wheatgrass hay at $35.51 per period.

Table 11. Costs and returns for forage types during 90 day third trimester production period with 1200 lb cow.

Costs/Returns		Early Crested Wheat Hay	Early Forage Barley Hay	Late Forage Barley Hay	Early Oat Forage Hay	Late Oat Forage Hay	Late Pea Forage Hay
Forage DM Wt	lbs/ac	1300.0	4733.0	5133.0	4667.0	5667.0	4650.0
Production Costs	$/ac	26.50	68.21	70.35	69.17	74.53	86.87
Forage DM Costs	$/ton	40.80	28.80	27.40	29.60	26.40	37.40
Crude Protein	%	14.5	13.0	9.2	11.5	7.8	14.4
CP Yield	lb/ac	189	606	468	535	435	685
CP Costs	$/lb	0.14	0.11	0.15	0.13	0.17	0.13
Forage/day	lbs/d	12.9	14.4	20.3	16.3	24.0	13.0
Land Area	ac	0.89	0.27	0.36	0.31	0.38	0.25
Roughage/day	lbs/d	11.1	9.6	3.7	7.7	-	11.0
Forage Costs	$/pp	23.59	18.42	25.33	21.44	28.32	21.72
Roughage Costs	$/pp	17.48	15.12	5.83	12.13	-	17.33
Total Feed Costs	$/pp	41.07	33.54	31.16	33.57	28.32	39.05
Cost/day	$/d	0.46	0.37	0.35	0.37	0.32	0.43
Calf Wt Gain	lbs/pp	70.00	70.00	70.00	70.00	70.00	70.00
Wt. Value @$1.00/lb	$	70.00	70.00	70.00	70.00	70.00	70.00
Net Return/C-C pr	$	28.93	36.46	38.84	36.43	41.68	30.95
Net Return/Acre	$	35.51	135.04	107.89	117.52	109.68	123.80
Calf Gain Cost	$/lb	0.59	0.48	0.45	0.48	0.41	0.56

Early Lactation

The early lactation production period was 45 days during early spring from 20 March to 4 May. The early lactation period has the greatest nutritional requirements of the six production periods because the birth of the calf initiates production of increasing amounts of milk and the reproductive organs require repair and preconditioning to promote the rapid onset of the estrus cycle. Cows gaining weight during this period will produce milk in quantities at or near the animals' genetic potential. Cows increasing in body condition will have adequate time to complete at least one estrus cycle prior to the start of the breeding season; this rapid recovery improves the percentage of cows that conceive in the first cycle of the breeding season (BCRC 1999). Feeding forages containing insufficient nutrients during this period causes a reduced cow body condition that results in milk production at levels below the animals' genetic potential and in a delayed onset of estrual activity so that the period between calving and the first estrus cycle is lengthened and conception rates in the cow herd are reduced. During the 45 day early lactation period, a 1200 lb cow with calf born in mid March requires 1215 lbs of forage dry matter, 713.25 lbs of energy (TDN), and 122.85 lbs of crude protein, with daily intake of 27 lbs dry matter, 2.37 lbs crude protein (table 7), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 45 day early lactation production period (table 12). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 18.8 lbs/day to provide 2.7 lbs CP/day, with 8.2 lbs/day of roughage added to the ration. Production of 846.00 lbs of early cut crested wheatgrass hay would require 0.65 acres at a cost of $17.23/period, with roughage costs at $6.46/period, the total feed cost was $23.69/period, or $0.53/day. Calf weight gain was 1.90lbs/day and accumulated weight gain was 85.50 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $85.50 per calf. The net returns after feed costs were $61.81/cow-calf pair and $95.09/acre. The cost of calf weight gain was $0.28/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 45 day early lactation production period (table 12). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 21.0 lbs/day to provide 2.7 lbs CP/day, with 6.0 lbs/day of roughage added to the ration. Production of 945.00 lbs of early cut forage barley hay would require 0.20 acres at a cost of $13.64/period, with roughage costs at $4.73/period, the total feed cost was $18.37/period, or $0.41/day. Calf weight gain was 1.90lbs/day and accumulated weight gain was 85.50 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $85.50 per calf. The net returns after feed costs were $67.31/cow-calf pair and a very high gain of $335.65/acre. The cost of calf weight gain was $0.21/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 45 day early lactation production period (table 12). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 23.7 lbs/day to provide 2.7 lbs CP/day, with 3.3 lbs/day of roughage added to the ration. Production of 1066.50 lbs of early cut oat forage hay would require 0.23 acres at a cost of $15.91/period, with roughage costs at $2.60/period, the total feed cost was $18.51/period, or $0.41/day. Calf weight gain was 1.90lbs/day and accumulated weight gain was 85.50 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $85.50 per calf. The net returns after feed costs were $66.99/cow-calf pair and a high gain of $291.26/acre. The cost of calf weight gain was $0.22/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 45 day early lactation production period (table 12). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $37.40/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 19.0 lbs/day to provide 2.7 lbs CP/day, with 8.0

lbs/day of roughage added to the ration. Production of 855.00 lbs of late cut pea forage hay would require 0.18 acres at a cost of $15.64/period, with roughage costs at $6.30/period, the total feed cost was $21.94/period, or $0.49/day. Calf weight gain was 1.90lbs/day and accumulated weight gain was 85.50 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $85.50 per calf. The net returns after feed costs were $63.56/cow-calf pair and a very high gain of $353.11/acre. The cost of calf weight gain was $0.26/lb.

During the early lactation period the total feed cost were significantly low for the three annual forage hay types at a mean $19.61 per period, and $0.44 per day and was significantly high for the early crested wheatgrass hay at $23.69 per period, and $0.53 per day. Net return per cow-calf pair was significantly high for the three annual forage hay types at a mean $65.89 per period and was significantly low for the early crested wheatgrass hay at $61.81 per period. Net return per acre were significantly high for the three annual forage hay types at a mean $326.67 per period and was significantly low for the early crested wheatgrass hay at $95.09 per period.

Table 12. Costs and returns for forage types during 45 day early lactation production period with 1200 lb cow and calf born in mid March.

Costs/Returns		Early Crested Wheat Hay	Early Forage Barley Hay	Early Oat Forage Hay	Late Pea Forage Hay
Forage DM Wt	lbs/ac	1300.0	4733.0	4667.0	4650.0
Production Costs	$/ac	26.50	68.21	69.17	86.87
Forage DM Costs	$/ton	40.80	28.80	29.60	37.40
Crude Protein	%	14.5	13.0	11.5	14.4
CP Yield	lb/ac	189	606	535	685
CP Costs	$/lb	0.14	0.11	0.13	0.13
Forage/day	lbs/d	18.8	21.0	23.7	19.0
Land Area	ac	0.65	0.20	0.23	0.18
Roughage/day	lbs/d	8.2	6.0	3.3	8.0
Forage Costs	$/pp	17.23	13.64	15.91	15.64
Roughage Costs	$/pp	6.46	4.73	2.60	6.30
Total Feed Costs	$/pp	23.69	18.37	18.51	21.94
Cost/day	$/d	0.53	0.41	0.41	0.49
Calf Wt Gain	lbs/pp	85.50	85.50	85.50	85.50
Wt. Value @$1.00/lb	$	85.50	85.50	85.50	85.50
Net Return/C-C pr	$	61.81	67.13	66.99	63.56
Net Return/Acre	$	95.09	335.65	291.26	353.11
Calf Gain Cost	$/lb	0.28	0.21	0.22	0.26

Spring Lactation

The spring lactation production period was 28 days during spring from 4 May to 1 June. The spring lactation period has nutritional requirements slightly reduced from those of the previous period. The quantity of milk produced continues to increase until the peak is reached during the later part of the second month or the early part of the third month after calving (BCRC 1999). Cows gaining weight during this period produce milk in quantities at or near the animals' genetic potential. Cows not gaining weight produce less than their genetic potential. Providing harvested forages or pasture forages with high nutrient content prior to and during breeding season stimulates ovulation in the cows; cows with improving body condition start estrus cycles earlier and can rebreed in 80 to 85 days after calving (BCRC 1999). The rate of calf weight gain continues to increase during the spring period. Calves that are around a month old in early May have developed enough to take advantage of the high levels of milk produced by cows grazing high quality forage on domesticated grass spring complementary pastures and add weight at high rates. During the 28 day spring lactation period, a 1200 lb cow with calf born in mid March requires 840 lbs of forage dry matter, 426.44 lbs of energy (TDN), and 70.28 lbs of crude protein, with daily intake of 30 lbs dry matter, 2.51 lbs crude protein (tables 7 and 8), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 17.3 lbs/day to provide 2.5 lbs CP/day, with 12.7 lbs/day of roughage added to the ration. Production of 484.40 lbs of early cut crested wheatgrass hay would require 0.37 acres at a cost of $9.81/period, with roughage costs at $6.22/period, the total feed cost was $16.03/period, or $0.57/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 56.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $56.00 per calf. The net returns after feed costs were $39.97/cow-calf pair and $108.03/acre. The cost of calf weight gain was $0.29/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 19.3 lbs/day to provide 2.5 lbs CP/day, with 10.7 lbs/day of roughage added to the ration. Production of 540.40 lbs of early cut forage barley hay would require 0.11 acres at a cost of $7.50/period, with roughage costs at $5.24/period, the total feed cost was $12.74/period, or $0.46/day. Calf weight gain was 2.00 lbs/day and accumulated weight gain was 56.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $56.00 per calf. The net returns after feed costs were $43.26/cow-calf pair and a very high gain of $393.27/acre. The cost of calf weight gain was $0.23/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 21.8 lbs/day to provide 2.5 lbs CP/day, with 8.2 lbs/day of roughage added to the ration. Production of 610.40 lbs of early cut oat forage hay would require 0.13 acres at a cost of $8.99/period, with roughage costs at $4.02/period, the total feed cost was $13.01/period, or $0.46/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 56.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $56.00 per calf. The net returns after feed costs were $42.99/cow-calf pair and a high gain of $330.69/acre. The cost of calf weight gain was $0.23/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $35.39/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 17.4 lbs/day to provide 2.5 lbs CP/day, with

12.6 lbs/day of roughage added to the ration. Production of 487.20 lbs of late cut pea forage hay would require 0.11 acres at a cost of $9.56/period, with roughage costs at $6.17/period, the total feed cost was $15.73/period, or $0.56/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 56.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $56.00 per calf. The net returns after feed costs were $40.27/cow-calf pair and a high gain of $366.09/acre. The cost of calf weight gain was $0.28/lb.

Crested Wheatgrass One Pasture

Crested wheatgrass spring complementary traditional one pasture treatment was grazed from 4 May to 1 June and was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 16.8%. Crested wheatgrass one pasture had rent costs of $8.76/ac, forage dry matter costs of $35.39/ton, and crude protein costs of $0.11/lb. Traditional crested wheatgrass pasture was stocked at 2.33 ac/AUM (2.14 ac/AU). Allocation of 30 lbs/d provided 840 lbs forage/period and 5.0 lbs/d crude protein/cow-calf pair. Forage removal rate was 993 lbs or 35.5 lbs/d/cow-calf pair. Total feed cost was $18.75/period, or $0.67/day. Calf weight gain was 2.57 lbs/d, 32.9 lbs/ac, accumulated weight gain was 72.67 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $72.67 per calf. The net returns after feed costs were $53.92/cow-calf pair and $25.20/acre. The cost of calf weight gain was $0.26/lb.

Crested Wheatgrass Two Pasture

Crested wheatgrass spring complementary biologically effective two pasture switchback treatment was grazed from 4 May to 1 June and was evaluated during the 28 day spring lactation production period (table 13). The crude protein content was 17.1%. Crested wheatgrass two pasture switchback had rent costs of $8.76/ac, forage dry matter costs of $32.11/ton, and crude protein costs of $0.09/lb. Biologically effective crested wheatgrass pastures were stocked at 1.30 ac/AUM (1.20 ac/AU). Allocation of 30 lbs/d provided 840 lbs forage/period and 5.0 lbs/d crude protein/cow-calf pair. Forage removal rate was 1372 lbs or 49.0 lbs/d/cow-calf pair. Total feed cost was $10.51/period, or $0.38/day. Calf weight gain was 2.61 lbs/d, 66.6 lbs/ac, accumulated weight gain was 76.45 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $76.45 per calf. The net returns after feed costs were $65.94/cow-calf pair and $54.95/acre. The cost of calf weight gain was $0.14/lb.

During the spring lactation period the total feed cost were not significantly different among the harvested forage hay types at a mean $14.38 per period, and $0.51 per day. The total feed cost was significantly low for the crested wheatgrass two pasture switchback strategy at $10.51 per period, and $0.38 per day and was significantly high for the crested wheatgrass one pasture strategy at $18.75 per period, and $0.67 per day. Net return per cow-calf pair was significantly high for the crested wheatgrass two pasture switchback strategy at $65.94 per period and was not significantly different for the four harvested forage hay types at a mean $41.62 per period. Net return per acre was significantly high for the early forage barley hay at $393.27 per period and was significantly low for the crested wheatgrass one pasture strategy at $25.20 per period. The net return per acre was significantly lower for the early crested wheatgrass hay at $108.03 per period than those for the other three harvested forage hay types.

Table 13. Costs and returns for forage types during 28 day spring lactation production period with 1200 lb cow and calf born in mid March.

Costs/Returns		Early Crested Wheat Hay	Early Forage Barley Hay	Early Oat Forage Hay	Late Pea Forage Hay	Crested Wheat One Pasture	Crested Wheat Two Pasture
Forage DM Wt	lbs/ac	1300.0	4733.0	4667.0	4650.0	495.0	545.6
Production Costs	$/ac	26.50	68.21	69.17	86.87	8.76	8.76
Forage DM Costs	$/ton	40.80	28.80	29.60	35.39	35.39	32.11
Crude Protein	%	14.5	13.0	11.5	14.4	16.8	17.1
CP Yield	lb/ac	189	606	535	685	54	93
CP Costs	$/lb	0.14	0.11	0.13	0.13	0.11	0.09
Forage/day	lbs/d	17.3	19.3	21.8	17.4	30	30
Land Area	ac	0.37	0.11	0.13	0.11	2.14	1.20
Roughage/day	lbs/d	12.7	10.7	8.2	12.6	-	-
Forage Costs	$/pp	9.81	7.50	8.99	9.56	18.75	10.51
Roughage Costs	$/pp	6.22	5.24	4.02	6.17	-	-
Total Feed Costs	$/pp	16.03	12.74	13.01	15.73	18.75	10.51
Cost/day	$/d	0.57	0.46	0.46	0.56	0.67	0.38
Calf Wt Gain	lbs/pp	56.00	56.00	56.00	56.00	72.67	76.45
Wt. Value @$1.00/lb	$	56.00	56.00	56.00	56.00	72.67	76.45
Net Return/C-C pr	$	39.97	43.26	42.99	40.27	53.92	65.94
Net Return/Acre	$	108.03	393.27	330.69	366.09	25.20	54.95
Calf Gain Cost	$/lb	0.29	0.23	0.23	0.28	0.26	0.14

Summary Lactation

The summer lactation production period was 135 days during summer from 1 June to 14 October. The summer lactation period has nutritional requirements 41% to 72% above maintenance. The greater part of the additional nutrients is for the production of milk for the nursing calf, and a smaller amount is for the support of an embryo at the early stages of development. The nutritional quality of the forage during the summer plays a critical role in maintaining the pregnancy. Cows maintaining or improving body condition have lower rates of embryo loss than cows losing body condition (BCRC 1999). The quantity of milk produced during the summer period declines from peak levels, however, the nutritional quality of the forage affects the rate of decline. If the forage quality is at or above the animals' nutritional requirements, cows can maintain milk production near their genetic potential during most of the lactation period (BCRC 1999). Cows with higher milk production produce heavier calves at weaning. Cows grazing pasture treatments with forage quality insufficient to meet animal nutritional requirements have milk production below their genetic potential and produce calves that are lighter at weaning and have higher cost per pound of weight gained. During the 135 day summer lactation period, a 1200 lb cow with calf born in mid March requires 4050 lbs of forage dry matter, 2056.05 lbs of energy (TDN), and 338.85 lbs of crude protein, with daily intake of 30 lbs dry matter, 2.51 crude protein (tables 7 and 8), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 17.3 lbs/day to provide 2.5 lbs CP/day, with 12.7 lbs/day of roughage added to the ration. Production of 2335.50 lbs of early cut crested wheatgrass hay would require 1.80 acres at a cost of $47.70/period, with roughage costs at $30.00/period, the total feed cost was $77.70/period, or $0.58/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 270.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $270.00 per calf. The net returns after feed costs were $192.30/cow-calf pair and $106.83/acre. The cost of calf weight gain was $0.29/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 19.3 lbs/day to provide 2.5 lbs CP/day, with 10.7 lbs/day of roughage added to the ration. Production of 2605.50 lbs of early cut forage barley hay would require 0.55 acres at a cost of $37.52/period, with roughage costs at $25.28/period, the total feed cost was $62.80/period, or $0.47/day. Calf weight gain was 2.00 lbs/day and accumulated weight gain was 270.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $270.00 per calf. The net returns after feed costs were $207.20/cow-calf pair and a very high gain of $376.73/acre. The cost of calf weight gain was $0.23/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 21.8 lbs/day to provide 2.5 lbs CP/day, with 8.2 lbs/day of roughage added to the ration. Production of 2943.00 lbs of early cut oat forage hay would require 0.63 acres at a cost of $43.58/period, with roughage costs at $19.37/period, the total feed cost was $62.95/period, or $0.47/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 270.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $270.00 per calf. The net returns after feed costs were $207.05/cow-calf pair and a high gain of $328.65/acre. The cost of calf weight gain was $0.23/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $35.39/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 17.4 lbs/day to provide 2.5 lbs CP/day, with 12.6 lbs/day of roughage added to the ration. Production of 2349.00 lbs of late cut pea forage hay would require 0.51 acres at a cost of $44.30/period, with roughage costs at $29.77/period, the total feed cost was $74.07/period, or $0.55/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 270.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $270.00 per calf. The net returns after feed costs were $195.93/cow-calf pair and a high gain of $384.18/acre. The cost of calf weight gain was $0.27/lb.

Native Range Seasonlong Pasture

Native range traditional seasonlong pasture treatment was grazed from 1 June to 14 October and was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 8.4%. Native range seasonlong pasture had rent costs of $8.76/ac, forage dry matter costs of $58.33/ton, and crude protein costs of $0.35/lb. Traditional native range seasonlong pasture was stocked at 2.58 ac/AUM (11.43 ac/AU). Allocation of 30 lbs/d provided 4050.00 lbs forage/period and 2.5 lbs/d crude protein/cow-calf pair. Total feed cost was $100.13/period, or $0.74/day. Calf weight gain was 2.65 lbs/d, 30.61 lbs/ac, accumulated weight gain was 354.37 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $354.37 per calf. The net returns after feed costs were $254.24/cow-calf pair and $22.24/acre. The cost of calf weight gain was $0.28/lb.

Native Range Twice-over Pasture

Native range biologically effective twice-over pasture system was grazed from 1 June to 14 October and was evaluated during the 135 day summer lactation production period (table 14). The crude protein content was 9.8%. Native range twice-over pasture system had rent costs of $8.76/ac, forage dry matter costs of $51.92/ton, and crude protein costs of $0.26/lb. Biologically effective native range twice-over pastures were stocked at 2.26 ac/AUM (10.22 ac/AU). Allocation of 30 lbs/d provided 4050.00 lbs forage/period and 2.9 lbs/d crude protein/cow-calf pair. Total feed cost was $89.53/period, or $0.66/day. Calf weight gain was 2.89 lbs/d, 37.66 lbs/ac, accumulated weight gain was 380.47 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $380.47 per calf. The net returns after feed costs were $290.94/cow-calf pair and $28.47/acre. The cost of calf weight gain was $0.24/lb.

During the summer lactation period the total feed cost were significantly low for the early forage barley hay at $62.80 per period, and $0.47 per day and the early oat forage hay at $62.95 per period, and $0.47per day and was significantly high for the native range seasonlong pasture strategy at $100.13 per period, and $0.74 per day. Net return per cow-calf pair was significantly high for the native range twice-over strategy at $290.94 per period and was significantly low for the early crested wheatgrass hay at $192.30 per period. Net return per acre was significantly high for the late pea forage barley hay at $384.18 per period and was significantly low for the native range seasonlong pasture strategy at $22.24 per period.

Table 14. Costs and returns for forage types during 135 day summer lactation production period with 1200 lb cow and calf born in mid March.

Costs/Returns		Early Crested Wheat Hay	Early Forage Barley Hay	Early Oat Forage Hay	Late Pea Forage Hay	Native Range Seasonlong Pasture	Native Range Twice-over Pasture
Forage DM Wt	lbs/ac	1300.0	4733.0	4667.0	4650.0	300.4	337.4
Production Costs	$/ac	26.50	68.21	69.17	86.87	8.76	8.76
Forage DM Costs	$/ton	40.80	28.80	29.60	35.39	58.33	51.92
Crude Protein	%	14.5	13.0	11.5	14.4	8.4	9.8
CP Yield	lb/ac	189	606	535	685	25	33
CP Costs	$/lb	0.14	0.11	0.13	0.13	0.35	0.26
Forage/day	lbs/d	17.3	19.3	21.8	17.4	30	30
Land Area	ac	1.80	0.55	0.63	0.51	11.43	10.22
Roughage/day	lbs/d	12.7	10.7	8.2	12.6	-	-
Forage Costs	$/pp	47.70	37.52	43.58	44.30	100.13	89.53
Roughage Costs	$/pp	30.00	25.28	19.37	29.77	-	-
Total Feed Costs	$/pp	77.70	62.80	62.95	74.07	100.13	89.53
Cost/day	$/d	0.58	0.47	0.47	0.55	0.74	0.66
Calf Wt Gain	lbs/pp	270.00	270.00	270.00	270.00	354.37	380.47
Wt. Value @$1.00/lb	$	270.00	270.00	270.00	270.00	354.37	380.47
Net Return/C-C pr	$	192.30	207.20	207.05	195.93	254.24	290.94
Net Return/Acre	$	106.83	376.73	328.65	384.18	22.24	28.47
Calf Gain Cost	$/lb	0.29	0.23	0.23	0.27	0.28	0.24

Fall Lactation

The fall lactation production period was 30 days during fall from 14 October to 13 November. The fall lactation period has nutritional requirements unchanged from the summer lactation period. The greater part of the required nutrient above maintenance is for the production of milk for the nursing calf, and a smaller amount is for fetus development. The nutritional quality of the forage affects the quantity of milk produced. If forage quality is at or near animal nutritional requirements, milk production can be fairly high and rate of calf weight gain can be satisfactory (BCRC 1999). Forage quantity of mature perennial grasses on traditionally managed pastures is below the requirements of a lactating cow. Forage feed costs increase when the nutrient quality of the grass or harvested forage provided does not meet the nutritional requirements of the cow. Cows lose body weight and body condition when body reserves are converted into milk production. The level of milk production and the rate of calf weight gain were low; the result is higher costs per pound of calf weight gained. During the 30 day fall lactation period, a 1200 lb cow with calf born in mid March requires 900 lbs of forage dry matter, 456.9 lbs of energy (TDN), and 75.3 lbs of crude protein, with daily intake of 30 lbs dry matter, 2.51 lbs crude protein (tables 7 and 8), and adequate amounts of minor essential elements (table 9).

Early Crested Wheatgrass Hay

Crested wheatgrass hay cut early during the boot stage was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 14.5%. Early cut crested wheatgrass hay had production costs of $26.50/ac, forage dry matter costs of $40.80/ton, and crude protein costs of $0.14/lb. Early cut crested wheatgrass hay would be fed at 17.3 lbs/day to provide 2.5 lbs CP/day, with 12.7 lbs/day of roughage added to the ration. Production of 519.00 lbs of early cut crested wheatgrass hay would require 0.40 acres at a cost of $10.60/period, with roughage costs at $6.67/period, the total feed cost was $17.27/period, or $0.58/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $42.73/cow-calf pair and $106.83/acre. The cost of calf weight gain was $0.29/lb.

Early Forage Barley Hay

Forage barley hay cut early at the beginning of the milk stage was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 13.0%. Early cut forage barley hay had production costs of $68.21/ac, forage dry matter costs of $28.80/ton, and crude protein costs of $0.11/lb. Early cut forage barley hay would be fed at 19.3 lbs/day to provide 2.5 lbs CP/day, with 10.7 lbs/day of roughage added to the ration. Production of 579.00 lbs of early cut forage barley hay would require 0.12 acres at a cost of $8.19/period, with roughage costs at $5.62/period, the total feed cost was $13.81/period, or $0.46/day. Calf weight gain was 2.00 lbs/day and accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $46.19/cow-calf pair and a very high gain of $384.92/acre. The cost of calf weight gain was $0.23/lb.

Late Forage Barley Hay

Forage barley hay cut late at the hard dough stage was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 9.2%. Late cut forage barley hay had production costs of $70.35/ac, forage dry matter costs of $27.40/ton, and crude protein costs of $0.15/lb. Late cut forage barley hay would be fed at 27.3 lbs/day to provide 2.5 lbs CP/day, with 2.7 lbs/day of roughage added to the ration. Production of 819.00 lbs of late cut forage barley hay would require 0.16 acres at a cost of $11.26/period, with roughage costs at $1.42/period, the total feed cost was $12.68/period, or $0.42/day. Calf weight gain was 2.00 lbs/day and accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $47.32/cow-calf pair and a high gain of $295.75/acre. The cost of calf weight gain was $0.21/lb.

Early Oat Forage Hay

Oat forage hay cut early at the beginning of the milk stage was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 11.5%. Early cut oat forage hay had production costs of $69.17/ac, forage dry matter costs of $29.60/ton, and crude protein costs of $0.13/lb. Early cut oat forage hay would be fed at 21.8 lbs/day to provide 2.5 lbs CP/day, with 8.2 lbs/day of roughage added to the ration. Production of 654.00 lbs of early cut oat forage hay would require 0.14 acres at a cost of $9.68/period, with roughage costs at $4.31/period, the total feed cost was $14.00/period, or $0.47/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $46.00/cow-calf pair and a high gain of $328.65/acre. The cost of calf weight gain was $0.23/lb.

Late Pea Forage Hay

Pea forage hay cut late at the full growth stage before pods start to fill was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 14.4%. Late cut pea forage hay had production costs of $86.87/ac, forage dry matter costs of $37.40/ton, and crude protein costs of $0.13/lb. Late cut pea forage hay would be fed at 17.4 lbs/day to provide 2.5 lbs CP/day, with 12.6 lbs/day of roughage added to the ration. Production of 522.00 lbs of late cut pea forage hay would require 0.11 acres at a cost of $9.56/period, with roughage costs at $6.62/period, the total feed cost was $16.18/period, or $0.54/day. Calf weight gain was 2.00lbs/day and accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $43.82/cow-calf pair and a very high gain of $398.36/acre. The cost of calf weight gain was $0.27/lb.

Spring Seeded Winter Cereal Pasture

Winter rye was seeded during the spring planting period, separated by electric fence in four units that contained forage for one week of grazing each, for a total treatment from 14 October to 13 November and was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 12.2%. Spring seeded winter cereal pastures had production costs of $41.75/ac, forage dry matter costs of $43.77/ton, and crude protein costs of $0.18/lb. Winter cereal pastures were stocked at 0.48 ac/AUM (0.47 ac/AU). Allocation of 30 lbs/d provided 900 lbs forage/period and 3.7 lbs/d crude protein/cow-calf pair. Total feed cost was $19.70/period, or $0.66/day. Calf weight gain was 2.00 lbs/d, 127.66 lbs/ac, accumulated weight gain was 60.00 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $60.00 per calf. The net returns after feed costs were $40.30/cow-calf pair and $85.74/acre. The cost of calf weight gain was $0.33/lb.

Winter rye is not the only annual winter cereal that would provide forage during the fall lactation production period, however, it was one of the desired winter cereals that had seed available in western North Dakota. Winter wheat and winter triticale seed was also available, however, livestock prefer winter rye forage to winter wheat or winter triticale forage. The winter triticale would produce greater forage weight per acre, the winter wheat would produce mid range forage weight per acre, and the winter rye would produce the lowest forage weight per acre. However, when all three winter cereal types are available, cattle will walk past winter triticale and winter wheat to get to the winter rye.

Other winter cereals that have promise as a fall forage source but still have problems of seed availability in the northern plains is winter barley and winter oat. The desired winter oat is Cosaque black oat (Avena sativa) which should not be confused with old European black winter oat (Avena strigosa) which has ergot and fusarium head blight problems. Until seed dealers supply winter barley and winter oat seed to the northern plains region, acquisition of seeds of winter barley and winter oat will require travel to the region where they are produced during the normal harvest time.

Altai Wildrye Pasture

Altai widrye pasture was grazed from 14 October to 13 November and was evaluated during the 30 day fall lactation production period (table 15). The crude protein content was 10.2%. Altai wildrye pastures had rent costs of $8.76/ac, forage dry matter costs of $22.31/ton, and crude protein costs of $0.11/lb. Altai wildrye pastures were stocked at 1.41 ac/AUM (1.39 ac/AU). Allocation of 30 lbs/d provided 900 lbs forage/period and 3.1 lbs/d crude protein/cow-calf pair. Total feed cost was $12.18/period, or $0.41/day. Calf weight gain was 1.82 lbs/d, 37.12 lbs/ac, accumulated weight gain was 50.34 lbs. When calf accumulated weight was assumed to have a low value of $1.00/lb, the gross return was $50.34 per calf. The net returns after feed costs were $38.16/cow-calf pair and $27.45/acre. The cost of calf weight gain was $0.24/lb.

During the fall lactation period the total feed cost were significantly low for the Altai wildrye pasture at $12.18 per period, and $0.41 per day and for the late forage barley hay at $12.68 per period, and $0.42 per day and were significantly high for the spring seeded winter cereal pasture at $19.70 per period, and $0.66 per day and for the early crested wheatgrass hay at $17.27 per period, and $0.58 per day. Net return per cow-calf pair was significantly high for the late forage barley hay at $47.32 per period and was significantly low for the Altai wildrye pasture at $38.16 per period. Net return per acre was significantly high for the late pea forage hay at $398.36 per period and was significantly low for the Altai wildrye pasture at $27.45. The net return per acre for the late forage barley hay was significantly lower than that for the other annual forage hay types.

Late crested wheatgrass hay had the lowest content of crude protein at 6.4%, the lowest yield at 102 lbs/ac, and the highest cost at $0.28/lb and was deficient of crude protein during all cow production periods except the dry gestation period.

Late oat forage hay had the second lowest content of crude protein at 7.8%, and the second highest cost at $0.17/lb, and was deficient of crude protein during all cow production periods except the dry gestation and third trimester periods.

Late forage barley hay had the third lowest content of crude protein at 9.2%, and was deficient of crude protein during the early lactation period and was borderline deficient of crude protein during the other three lactation periods, however, late forage barley hay was fed during the fall lactation period because it had a low total forage feed cost.

Early forage barley hay, early oat forage hay, and late pea forage hay were excellent annual forage hay types with consistently low total feed cost and high net return per cow-calf pair and net return per acre.

Table 15. Costs and returns for forage types during 30 day fall lactation production period with 1200 lb cow and calf born in mid March.

Costs/Returns		Early Crested Wheat Hay	Early Forage Barley Hay	Late Forage Barley Hay	Early Oat Forage Hay	Late Pea Forage Hay	Spring Seeded Winter Cereal Pasture	Altai Wildrye Pasture
Forage DM Wt	lbs/ac	1300.0	4733.0	5133.0	4667.0	4650.0	1908.0	785.25
Production Costs	$/ac	26.50	68.21	70.35	69.17	86.87	41.75	8.76
Forage DM Costs	$/ton	40.80	28.80	27.40	29.60	37.40	43.77	22.31
Crude Protein	%	14.5	13.0	9.2	11.5	14.4	12.2	10.2
CP Yield	lb/ac	189	606	468	535	685	233	80
CP Costs	$/lb	0.14	0.11	0.15	0.13	0.13	0.18	0.11
Forage/day	lbs/d	17.3	19.3	27.3	21.8	17.4	30	30
Land Area	ac	0.40	0.12	0.16	0.14	0.11	0.47	1.39
Roughage/day	lbs/d	12.7	10.7	2.7	8.2	12.6	-	-
Forage Costs	$/pp	10.60	8.19	11.26	9.68	9.56	19.70	12.18
Roughage Costs	$/pp	6.67	5.62	1.42	4.31	6.62	-	-
Total Feed Costs	$/pp	17.27	13.81	12.68	14.00	16.18	19.70	12.18
Cost/day	$/d	0.58	0.46	0.42	0.47	0.54	0.66	0.41
Calf Wt Gain	lbs/pp	60.00	60.00	60.00	60.00	60.00	60.00	50.34
Wt. Value @$1.00/lb	$	60.00	60.00	60.00	60.00	60.00	60.00	50.34
Net Return/C-C pr	$	42.73	46.19	47.32	46.00	43.82	40.30	38.16
Net Return/Acre	$	106.83	384.92	295.75	328.57	398.36	85.74	27.45
Calf Gain Cost	$/lb	0.29	0.23	0.21	0.23	0.27	0.33	0.24

Harvested Forage Management Strategies

Twelve-month forage management strategies were developed by using selected harvested forage types evaluated during the six range cow production periods. Four of these forage management strategies use single harvested forage types to demonstrate that harvested forages are not always the high cost forage they are assumed to be and to show that substantial revenue can be captured per acre by feeding harvested forage types.

Early Forage Barley Hay

The 12-month early forage barley hay strategy required a small total land area of 1.34 acres (table 16). The total forage costs were low at $91.40 per cow-calf pair, even with production costs at $68.21 per acre. The forage contained 13% crude protein, yielding a total of 830.88 lbs CP, meeting the cow requirements during each production period at a cost of $0.11 per pound CP. Roughage composed 36% of the total ration at a cost of $64.08. The total feed cost was $155.49 at a low rate of $30.93 per ton of the ration feed and $0.43 per day. The calf accumulated weight was a mean of all harvested forages evaluated at 566.50 pounds at a cost of $0.27 per pound. Net return per cow-calf pair was relatively high at $411.01 and net return per acre was extremely high at $306.72. Early cut forage barley hay would be an excellent harvested forage that would help modern high-performance cows produce at their genetic potential and that would improve the value captured from the land natural resources.

Early Oat Forage Hay

The 12-month early oat forage hay strategy required a small total land area of 1.54 acres (table 17). The total forage costs were low at $106.52 per cow-calf pair, even with production costs at $69.17 per acre. The forage contained 11.5% crude protein, yielding a total of 830.52 lbs CP, meeting the cows requirements during each production period at a cost of $0.13 per pound CP. Roughage composed 28% of the total ration at a cost of $49.55. The total feed cost was $156.08 at a low rate of $31.05 per ton of the ration feed and $0.43 per day. The calf accumulated weight was a mean of all harvested forages evaluated at 566.50 pounds at a cost of $0.28 per pound. Net return per cow-calf pair was relatively high at $410.42 and net return per acre was very high at $266.51. Early cut oat forage hay would be a very good harvested forage that would help modern high-performance cows produce at their genetic potential and that would improve the value captured from the land natural resources.

Late Pea Forage Hay

The 12-month late pea forage hay strategy required a very small total land are of only 1.24 acres (table 18). The total forage costs were low at $107.72 per cow-calf pair, even with production costs at $86.87 per acre. The forage contained 14.4% crude protein, yielding a total of 830.06 lbs CP, meeting the cows requirements during each production period at a cost of $0.13 per pound CP. Roughage composed 43% of the total ration at a cost of $75.06. The total feed cost was $182.79 at a low rate of $36.37 per ton of the ration feed and $0.50 per day. The calf accumulated weight was a mean of all harvested forages evaluated at 566.50 pounds at a cost of $0.32 per pound. Net return per cow-calf pair was relatively high at $383.71 and net return per acre was the highest of the harvested forages at $309.44. Late cut field pea forage hay would be an excellent harvested forage that would help modern high-performance cows produce at their genetic potential and that would improve the value captured from the land natural resources.

Early Crested Wheatgrass Hay

The 12-month early crested wheatgrass forage hay strategy required a modest total land are of 4.40 acres (table 19). The total forage costs were $116.60 per cow-calf pair, with moderate production costs at $26.50 per acre because it is a perennial grass hay. The forage contained 14.5% crude protein, yielding a total of 830.42 lbs CP, meeting the cows requirements during each production period at a cost of $0.14 per pound CP. Roughage composed 43% of the total ration at a cost of $75.70. The total feed cost was $192.32 at a low rate of $38.26 per ton of the ration feed and $0.53 per day. The calf accumulated weight was a mean of all harvested forages evaluated at 566.50 pounds at a cost of $0.34 per pound. Net return per cow-calf pair was relatively high at $374.10, but it was the lowest of the harvested forages, and net return per acre was modest at $85.02. Early cut crested wheatgrass hay was the most convenient harvested forage to put up and to deliver and was readily accepted by every cow. Crested wheatgrass hay cut during the boot stage is excellent forage that would help modern high-performance cows produce at their genetic potential and that would improve the value captured from the land natural resources.

The four harvested forage types evaluated for costs and returns during the six cow production periods (tables 10-15) all had moderate to low costs with moderate to high returns, and all harvested forage types would provide a positive profit margin. Late Pea Forage hay had the smallest land area at 1.24 acres, and the highest net return per acre at $309.44. Early Forage Barley Hay had the lowest cost per pound of crude protein at $0.11. Early Forage Barley Hay and Early Oat Forage Hay had the lowest total feed costs at $155.49 and $156.08, the lowest cost per pound of calf weight gain at $0.27 and $0.28, and they had the highest net returns per cow-calf pair at $411.01 and 410.42. Early Crested Wheatgrass Hay had the largest land area at 4.40 acres, the highest cost per pound of crude protein at $0.14, the highest total feed cost at $192.32, the highest cost per pound of calf weight gain at $0.34, the lowest net return per cow-calf pair at $374.10, and the lowest net return per acre at $87.02.

Harvested forages cut at the proper plant growth stage can provide excellent feed that meets the cows requirements, can be grown on relatively small land areas, and can return large profits per acre. Twelve-month harvested forage management strategies are not practical for most mature beef cow-calf operations but these four examples illustrate that despite relatively high production costs per acre, harvested forages can return impressive quantities of revenue. Furthermore, management strategies that feed harvested forages to cow-calf pairs for twelve months can be a viable stratagem for young producers to expedite reduction of large startup depts.

There are numerous other annual and perennial forage types that would also be excellent harvested forages. Under normal conditions of using annual forages, two or more different types would be selected that would work together in a simple cropland rotation scheme that would have different optimum planting and harvest dates but be able to use the same equipment. An example would be an early cut annual cereal forage and a late cut annual legume field pea seeded separately.

Table 16. Costs and Returns for 12 month Early Forage Barley Hay Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type					Early Forage Barley Hay			
Land Area	ac	0.09	0.27	0.20	0.11	0.55	0.12	1.34
Production Cost	$	6.14	18.42	13.64	7.50	37.52	8.19	91.40
Forage Wt	lb	425.50	1296.00	945.00	540.40	2605.50	579.00	6391.40
Forage Cost	$	6.14	18.42	13.64	7.50	37.52	8.19	91.40
Crude Protein	%	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Crude protein Wt	lb	55.32	168.48	122.85	70.25	338.72	75.72	830.88
Crude Protein/d	lb	1.50	1.87	2.73	2.51	2.51	2.51	2.28
Crude Protein Cost	$	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Roughage Wt	lb	462.50	864.00	270.00	299.60	1444.50	321.00	3661.60
Roughage Cost	$	8.09	15.12	4.73	5.24	25.28	5.62	64.08
Total Feed Cost	$	14.23	33.54	18.37	12.74	62.80	13.81	155.49
Cost/day	$	0.38	0.37	0.41	0.46	0.47	0.46	0.43
Acc. Calf Wt	lb	25.00	70.00	85.50	56.00	270.00	60.00	566.50
Return/c-c pr	$	10.77	36.46	67.13	43.26	207.20	46.19	411.01
Return/acre	$	119.67	135.04	335.65	393.27	376.73	384.92	306.72
Calf Wt Gain Cost	$	0.57	0.48	0.21	0.23	0.23	0.23	0.27

Table 17. Costs and Returns for 12 month Early Oat Forage Hay Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type					Early Oat Forage Hay			
Land Area	ac	0.10	0.31	0.23	0.13	0.63	0.14	1.54
Production Cost	$	6.92	21.44	15.91	8.99	43.58	9.68	106.52
Forage Wt	lb	481.00	1467.00	1066.50	610.40	2943.00	654.00	7221.90
Forage Cost	$	6.92	21.44	15.91	8.99	43.58	9.68	106.52
Crude Protein	%	11.5	11.5	11.5	11.5	11.5	11.5	11.5
Crude protein Wt	lb	55.32	168.71	122.65	70.20	338.45	75.21	830.52
Crude Protein/d	lb	1.50	1.87	2.73	2.51	2.51	2.51	2.28
Crude Protein Cost	$	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Roughage Wt	lb	407.00	693.00	148.50	229.60	1107.00	246.00	2831.10
Roughage Cost	$	7.12	12.13	2.60	4.02	19.37	4.31	49.55
Total Feed Cost	$	14.04	33.57	18.51	13.01	62.95	14.00	156.08
Cost/day	$	0.38	0.37	0.41	0.46	0.47	0.47	0.43
Acc. Calf Wt	lb	25.00	70.00	85.50	56.00	270.00	60.00	566.50
Return/c-c pr	$	10.96	36.43	66.99	42.99	207.05	46.00	410.42
Return/acre	$	109.60	117.52	291.26	330.69	328.65	328.57	266.51
Calf Wt Gain Cost	$	0.56	0.48	0.22	0.23	0.23	0.23	0.28

Table 18. Costs and Returns for 12 month Late Pea Forage Hay Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type					Late Pea Forage Hay			
Land Area	ac	0.08	0.25	0.18	0.11	0.51	0.11	1.24
Production Cost	$	6.95	21.72	15.64	9.56	44.30	9.56	107.72
Forage Wt	lb	381.10	1170.00	855.00	487.20	2349.00	522.00	5764.30
Forage Cost	$	6.95	21.72	15.64	9.56	44.30	9.56	107.72
Crude Protein	%	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Crude protein Wt	lb	54.88	168.48	123.12	70.16	338.26	75.17	830.06
Crude Protein/d	lb	1.48	1.87	2.74	2.51	2.51	2.51	2.27
Crude Protein Cost	$	0.13	0.13	0.13	0.14	0.13	0.13	0.13
Roughage Wt	lb	506.90	990.00	360.00	352.80	1701.00	378.00	4288.70
Roughage Cost	$	8.87	17.33	6.30	6.17	29.77	6.62	75.06
Total Feed Cost	$	15.82	39.05	21.94	15.73	74.07	16.18	182.79
Cost/day	$	0.43	0.43	0.49	0.56	0.55	0.54	0.50
Acc. Calf Wt	lb	25.00	70.00	85.50	56.00	270.00	60.00	566.50
Return/c-c pr	$	9.18	30.95	63.56	40.27	195.93	43.82	383.71
Return/acre	$	114.75	123.80	353.11	366.09	384.18	398.36	309.44
Calf Wt Gain Cost	$	0.63	0.56	0.26	0.28	0.27	0.27	0.32

Table 19. Costs and Returns for 12 month Early Crested Wheatgrass Hay Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type		Early Crested Wheatgrass Hay						
Land Area	ac	0.29	0.89	0.65	0.37	1.80	0.40	4.40
Production Cost	$	7.69	23.59	17.23	9.81	47.70	10.60	116.60
Forage Wt	lb	381.10	1161.00	846.00	484.40	2335.50	519.00	5727.00
Forage Cost	$	7.69	23.59	17.23	9.81	47.70	10.60	116.60
Crude Protein	%	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Crude protein Wt	lb	55.26	168.35	122.67	70.24	338.65	75.26	830.42
Crude Protein/d	lb	1.49	1.87	2.73	2.51	2.51	2.51	2.28
Crude Protein Cost	$	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Roughage Wt	lb	506.90	999.00	369.00	355.60	1714.50	381.00	4326.00
Roughage Cost	$	8.87	17.48	6.46	6.22	30.00	6.67	75.70
Total Feed Cost	$	16.56	41.07	23.69	16.03	77.70	17.27	192.32
Cost/day	$	0.45	0.46	0.53	0.57	0.58	0.58	0.53
Acc. Calf Wt	lb	25.00	70.00	85.50	56.00	270.00	60.00	566.50
Return/c-c pr	$	8.36	28.93	61.81	39.97	192.30	42.73	374.10
Return/acre	$	28.83	35.51	95.09	108.03	106.83	106.83	85.02
Calf Wt Gain Cost	$	0.67	0.59	0.28	0.29	0.29	0.29	0.34

Old Style VS. Modern Forage Management Strategies

The old style traditional concept of forage management consists of an accumulation of carryover practices that had been developed during past conditions when beef production was dominated with old style low-performance cattle. These old style concepts and paradigms have been slightly modified for the larger size of modern cows, however, the modern cows' increase in productivity and greater nutrient requirements have not been fully incorporated into these old style traditional forage management concepts, resulting in performance at levels well below the modern cows genetic potential.

The modern biologically effective concept of forage management coordinates forage defoliation by mechanical operation or partial defoliation by grazing animals with grass plant phenological growth stages in order to activate the internal plant growth mechanisms and the ecosystem biogeochemical processes performed by soil microorganisms and to capture the greatest weight of crude protein available per acre. These beneficial activities meet the biological and physiological requirements of the grass plants and soil microbes and provides all the required major essential nutrients to the modern cow permitting performance at the genetic potential and provides adequate quantities of milk to the calf permitting weight growth at the genetic potential level.

Twelve-month forage management strategies during the six range cow production periods were developed using six forage types managed by the old style traditional concept and six forage types managed by the modern biologically effective concept. Data for pasture forage types used during the spring, summer, and fall production periods were from Manske (2018b). The resulting costs and returns were evaluated to compare the effect on forage types and modern cow-calf pairs managed by two very different concepts of forage management. The effects from the biologically effective concept were further compared to the effects from the traditional concept of forage management were applied to hypothetical beef production operations of 5 sections in size.

Traditional Forage Management Strategy

The 12-month traditional forage management strategy required a large total land area of 18.78 acres per cow-calf pair (table 20). The total forage costs were $214.24 per cow-calf pair, with production costs at $11.41 per acre. The forage contained an average 8.8% crude protein, yielding a total of 872.48 lbs CP, at a cost of $0.25 per pound CP, meeting the cows requirements during each production period except the forage was deficient in crude protein during the 30 day fall lactation period. Roughage composed only 1.5% of the total feed at a cost of $2.60. The total feed cost was $216.84 at a rate of $43.14 per ton of the ration feed, $11.55 per acre, and $0.59 per day. The calf accumulated weight was a mean of all harvested forages evaluated during the 172 days of the nongrowing season plus the mean of traditional pasture gain during the 193 days of the growing season for a mean weight of 625.25 pounds at a cost of $0.35 per pound. Net return per cow-calf pair was relatively high at $408.41 and net return per acre was extremely low at $21.75. The traditional concept places priority on capturing the greatest weight of forage dry matter per acre resulting in low crude protein content requiring a larger land area per cow-calf pair causing the costs of forage and crude protein to be unnecessarily high. The low quality feed does not permit the cow to produce milk at her genetic potential resulting in calf weight gain to be lower than their genetic potential, increasing the cost of calf weight gain per pound and reducing the net return per cow-calf pair and per acre.

Biologically Effective Forage Management Strategy

The 12-month biologically effective forage management strategy required a total land area of 13.38 acres per cow-calf pair (table 21). The total forage costs were $154.72 per cow-calf pair, with production costs at $11.56 per acre. The forage contained an average 11.5% crude protein, yielding a total of 979.08 lbs CP, meeting the cows requirements during each production period at a cost of $0.16 per pound CP. Roughage composed 15% of the total forage feed at a cost of $26.47. The total feed cost was $181.19 at a low rate of $36.05 per ton of the forage feed, $13.54 per acre, and $0.50 per day. The calf accumulated weight was a mean of all harvested forages evaluated during the 172 days of the nongrowing season plus the mean of biologically effective pasture gain during the 193 days of the growing season for a mean weight of 687.76 pounds at a cost of $0.26 per pound. Net return per cow-calf pair was an extremely high gain at $506.57 and net return per acre was at $37.86. The biologically effective concept places priority on capturing the greatest weight of crude protein per acre reducing the amount of land area to feed a cow-calf pair, decreasing the costs per pound of crude protein and the forage feed costs. The high quality feed permits the cow to produce milk at or near her genetic potential resulting in calf weight gain to be at or near the genetic potential, decreasing the cost of calf weight gain per pound.

Value Captured by Forage Management Strategies

The resulting cost and return values determined from analysis of two different forage management concepts (tables 20 and 21) were applied to a modest hypothetical land base of 5 sections (3,200 acres) to discover any difference in the quantities of the values captured from the land resource (table 22).

The land area required to produce adequate quantities of forage for 1200 lb cows with calves was 18.78 acres per animal unit on the traditional concept permitting a cow herd of 170 head. The land area was 13.38 acres per animal unit (28.8% less) on the biologically effective concept permitting a cow herd of 239 head (40.6% larger). The captured crude protein on the traditional concept had a mean of 8.8% that yielded a total weight of 872.48 lbs CP per cow-calf pair at a cost of $0.25 per pound. The captured crude protein on the biologically effective concept had a mean of 11.5% (30.7% greater) that yielded a total weight of 979.08 lbs CP (12.2% more) per cow-calf pair at a cost of $0.16 per pound (36.0% lower). The additional crude protein available to each cow on the biologically effective concept permitted these cows to produce milk at or near the genetic potential for most of the grazing season that added 62.5 pounds to the weaning weight of the calves. The mean weaning weight of the calves on the traditional concept was 625.25 lbs per calf at a cost of $0.35 per pound with a total calf weight for 170 calves at 106,292.50 pounds that had a prorated gross return of $33.29 per acre. The mean weaning weight of calves on the biologically effective concept was 687.76 lbs per calf (10.0% heavier) at a cost of $0.26 per pound (25.7% less) with a total calf weight for 239 calves at 164,374.64 pounds (54.6% greater) that had a prorated gross return of $51.40 per acre (54.4% larger). The annual feed cost per cow-calf pair on the traditional concept was $216.84 with a total herd feed cost at $36,862.80. This feed cost was prorated at $11.55 per acre. The annual feed cost per cow-calf pair on the biologically effective concept was $181.19 (16.4% lower) with a total herd feed cost at $43,304.41 (only 17.5% greater). This feed cost was prorated at $13.54 per acre (17.2% larger). The net return per cow-calf pair on the traditional concept was $408.41 with a total herd net return minus the feed cost was $69,429.70. The prorated net return was $ 21.74 per acre. The net return per cow-calf pair on the biologically effective concept was $506.57 (24.0% greater) with a total herd net return minus the feed cost was $121,070.23 (74.4% greater). The prorated net return was $37.86 per acre (74.2% larger). The same size land base for a beef production operation yielded $51,640.53 per year more profit after paying the feed bill when the forage resource was managed by the biologically effective concept compared to that produced when the forage resource was managed by the traditional concept (table 22).

Biologically effective forage management could be implemented to help beef production operations to expand the size of the cow herd without needing to expand the land base. Biologically effective management of forages can provide a mechanism to produce relatively low cost, high quality forage that could feed about 40% more modern high performance cows producing at or near the genetic potential on a land base that was about 29% smaller per cow and that could greatly increase the net returns by about 74% (table 22).

Table 20. Costs and Returns for 12 month Traditional Forage Management Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type		Late Crested Wheat Hay`	Late Oat Forage Hay	Early Oat Forage Hay	Crested Wheat One Pasture	Native Range Seasonlong Pasture	Native Range Late Season Pasture	
Land Area	ac	0.56	0.38	0.23	2.14	11.43	4.04	18.78
Production Cost	$	15.74	28.32	15.91	18.75	100.13	35.39	214.24
Forage Wt	lb	888.00	2160.00	1066.50	840.00	4050.00	900.00	9904.50
Forage Cost	$	15.74	28.32	15.91	18.75	100.13	35.39	214.24
Crude Protein	%	6.4	7.8	11.5	16.8	8.4	4.8	8.8
Crude protein Wt	lb	56.83	168.48	122.65	141.12	340.20	43.20	872.48
Crude Protein/d	lb	1.54	1.87	2.73	5.04	2.52	1.44	2.39
Crude Protein Cost	$	0.28	0.17	0.13	0.13	0.29	0.82	0.25
Roughage Wt	lb	0.0	0.0	148.50	0.0	0.0	0.0	148.50
Roughage Cost	$	-	-	2.60	-	-	-	2.60
Total Feed Cost	$	15.74	28.32	18.51	18.75	100.13	35.39	216.84
Cost/day	$	0.43	0.32	0.41	0.67	0.74	1.18	0.59
Acc. Calf Wt	lb	25.00	70.00	85.50	72.65	354.37	17.73	625.25
Return/c-c pr	$	9.26	41.69	66.99	53.92	254.24	-17.66	408.41
Return/acre	$	16.54	109.68	291.26	25.20	22.24	-4.37	21.75
Calf Wt Gain Cost	$	0.63	0.41	0.22	0.26	0.28	2.00	0.35

Table 21. Costs and Returns for 12 month Biologically Effective Forage Management Strategy with 1200 lb cow and calf born mid March.

Days		Dry Gestation 37 d	Third Trimester 90 d	Early Lactation 45d	Spring Lactation 28 d	Summer Lactation 135 d	Fall Lactation 30 d	12-month Season 365 d
Forage Type		Late Forage Barley Hay	Early Forage Barley Hay	Late Pea Forage Hay	Crested Wheat Two Pasture	Native Range Twice-over Pasture	Altai Wildrye Pasture	
Land Area	ac	0.12	0.27	0.18	1.20	10.22	1.39	13.38
Production Cost	$	8.44	18.42	15.64	10.51	89.53	12.18	154.72
Forage Wt	lb	599.40	1296.00	855.00	840.00	4050.00	900.00	8540.40
Forage Cost	$	8.44	18.42	15.64	10.51	89.53	12.18	154.72
Crude Protein	%	9.2	13.0	14.4	17.1	9.8	10.2	11.5
Crude protein Wt	lb	55.14	168.48	123.12	143.64	396.90	91.80	979.08
Crude Protein/d	lb	1.49	1.87	2.74	5.13	2.94	3.06	2.68
Crude Protein Cost	$	0.15	0.11	0.13	0.07	0.23	0.13	0.16
Roughage Wt	lb	288.60	864.00	360.00	0.0	0.0	0.0	1512.60
Roughage Cost	$	5.05	15.12	6.30	-	-	-	26.47
Total Feed Cost	$	13.49	33.54	21.94	10.51	89.53	12.18	181.19
Cost/day	$	0.36	0.37	0.49	0.38	0.66	0.41	0.50
Acc. Calf Wt	lb	25.00	70.00	85.50	76.45	380.47	50.34	687.79
Return/c-c pr	$	11.51	36.46	63.56	65.94	290.94	38.16	506.57
Return/acre	$	95.92	135.04	353.11	54.95	28.47	27.45	37.86
Calf Wt Gain Cost	$	0.54	0.48	0.26	0.14	0.24	0.24	0.26

Table 22. Summary of costs and returns for the Biologically Effective concept compared to the Traditional concept of forage management strategies on a land base of 5 sections.

		Traditional Forage Management Strategy	Biologically Effective Forage Management Strategy	Percent Difference
Land Base	ac	3,200	3,200	Same
Land/Cow/Yr	ac	18.78	13.38	-28.8
No. Cows	hd	170	239	40.6
Crude Protein mean	%	8.8	11.5	30.7
Crude protein Wt/AU	lb	872.48	979.08	12.2
Crude Protein Cost/lb	$	0.25	0.16	-36.0
Acc. Calf Wt/hd	lb	625.25	687.76	10.0
Total Calf Wt/Yr	lb	106,292.50	164,374.64	54.6
Gross Return @ $1.00/lb	lb	106,292.50	164,374.64	54.6
Feed Cost/AU	$	216.84	181.19	-16.4
Total Feed Cost	$	36,862.80	43,304.41	17.5
Net Return/AU	$	408.41	506.57	24.0
Return-Feed Cost	$	69,429.70	121,070.23	74.4
Wt gain Cost/lb	$	0.35	0.26	-25.7
Gross Return/Acre	$	33.29	51.40	54.4
Feed Costs/Acre	$	11.55	13.54	17.2
Return-Feed Costs/Acre	$	21.74	37.86	74.2

Discussion

Beef producers have genetically improved the North American beef herd over the past 75 years, or so, in order to develop high quality feeder calves that are able to grow rapidly on primarily high energy grain based rations and to create flavorful, tender meat products. As a result, the continents cow herd has been selectively transformed into modern high-performance cows. The ration technologies utilized to quickly finish slaughter animals have been continuously improved. Unfortunately, forage management technologies have not simultaneously been developed and improved that match the available nutrients with the increased forage nutrients required by modern cows to routinely perform at their genetic potential. Weight production by modern high performance cows with calves has been severely stifled by the widespread use of slightly modified traditional forage management technologies and paradigms that had been developed for the old style low-performance livestock.

Modern cows produce calf weight at their genetic potential while the available forage contains an increase of nutrient at or slightly above the required quantities. A week of forage deficient in the required quantities of nutrients causes large reductions in productivity. Decreases in milk production caused by deficient quality forage cannot be recovered and this decrease in milk quantity results in calf weaning weights well below their genetic potential. In order to maintain modern cow and calf production at genetic potential, the forage management strategies must provide the nutrients at required quantities each day for 365 days per year and during no period longer than a few days can the forage be even slightly deficient in required nutrients.

Ruminant livestock have the ability to survive on very low quality forage, however, modern high-performance cows require high quality forage as pasture or from rations that meet their increased nutrient requirements in order to produce at their genetic potential. High quality forages do not have to have high costs. High quality forage types that provide low feed costs will have low captured crude protein costs per pound, low forage feed costs per day, and low calf weight gain costs per pound. Forage management practices that capture greater wealth from the land resources will have smaller land area requirements to feed cow-calf pairs and will have greater net returns per acre after feed costs. Crude protein is the valuable nutrient produced by forage plants on the land natural resources. Production of a pound of energy (TDN) requires a minuscule of the ecosystem resources compared to the production of a pound of crude protein. Forage feed costs should not be evaluated by the forage dry matter costs nor by other traditional costs that do not respond proportionally, with changes in the forage quantity of nutrients, mainly crude protein.

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The Scientific Explanation of How and Why the Twice-over Rotation Grazing Strategy is Biologically Effective Management for Grassland Ecosystems on the Northern Plains

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Grasslands are complex ecosystems; exceedingly more complex than the most complicated machines ever built by humans. Grassland ecosystems are comprised of biotic and abiotic components. The indispensable biotic components are grass vegetation, rhizosphere organisms, and domesticated graminivores which have biological and physiological requirements. The abiotic components include radiant energy from sunlight, the major essential elements of carbon, hydrogen, nitrogen, and oxygen, the minor essential elements of macro - and micro - nutrients required by living organisms, and the environmental conditions. Grass plants, rhizosphere organisms, and grazing graminivores have developed complex symbiotic relationships. Grazing graminivores depend on grass plants for nutritious forage. Grass plants depend on rhizosphere organisms for mineralization of essential elements from the soil organic matter. Rhizosphere organisms, which are achlorophyllous, depend on grass plants for short chain carbon energy that is exudated through the roots of lead tillers at vegetative growth stages following partial defoliation by grazing graminivores. Grass plants produce double the leaf biomass than is needed for photosynthesis in order to attract the vital partial defoliation by grazing graminivores on which they depend.

The indispensable rhizosphere microorganisms are responsible for the performance of the ecosystem biogeochemical processes that determine grassland ecosystem productivity and functionality. Biogeochemical processes transform stored essential elements from organic forms or ionic forms into plant usable mineral forms. Biogeochemcial processes capture replacement quantities of lost or removed major essential elements of carbon, hydrogen, nitrogen, and oxygen with assistance from active live plants and transform the replacement essential elements into storage as soil organic matter for later use. Biogeochemical processes decompose complex unusable organic material into compounds and then into reusable major and minor essential elements (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).

Perpetuation of life on earth requires that the abiotic major and minor essential elements be reused over and over. Recycling of the essential elements is performed by rhizosphere microorganisms. The essential elements are required for life to exist by ensuring growth and development of organisms and the maintenance of all life functions (table 1). Animals require twenty one elements and plants require seventeen elements. Sixteen of the same essential elements are required by both animals and plants. The major essential elements: carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) are required in very large amounts by animals and plants. A portion of the major essential elements is lost annually from grassland ecosystems by natural processes and a portion is removed from grassland ecosystems as weight biomass produced by insects and wildlife and as animal growth from essential elements transferred from grass plants to grazing livestock. When greater quantities of major essential elements are lost and removed than the quantities accumulated, the ecosystem degrades (declines). When greater quantities of major essential elements are accumulated than the quantities removed, the ecosystem aggrades (improves). Biologically effective management strategies can replenish the quantity of lost or removed major essential elements by capturing input essential elements from the surrounding environment through ecosystem biogeochemical processes performed by the indispensable rhizosphere microorganisms.

Animals and plants require large amounts of the same macronutrients: potassium (K), calcium (Ca), phosphorus (P), magnesium (Mg), and sulfur (S). Animals require an additional macronutrient: sodium (Na) and require chlorine (Cl) as a macronutrient. Warm season plants and cacti use some sodium (Na). Animals and plants require very small amounts of the same micronutrients or trace elements: iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni). Animals require additional micronutrients: iodine (I), cobalt (Co), selenium (Se), and chromium (Cr). Plants require an additional micronutrient: boron (B), and require chlorine (Cl) as a micronutrient. A few plants and rhizobia use some cobalt (Co).

The ecosystem source for all of the minor essential elements required by animals and plants is weathered parent material. The elemental content of the parent material greatly influences the quantity of macro - and micronutrients in the soil. The minor essential elements are stored in the soil organic matter as unavailable organic forms or as ions adsorbed by colloidal complexes and are biologically and chemically immobilized, respectively. While in these stable forms, the minor essential elements are not subjected to potential losses through volatilization or leaching movement (Legg 1975, Gibson 2009). The immobilized minor essential elements are made available through the ecosystem biogeochemical cycles performed by rhizosphere microorganisms (McGill and Cole 1981, Cheng and Johnson 1998, Manske 2012b, 2014c). The quantity of available minor essential elements is detemined by the recycling rates of soil organic matter decomposition and mineralization that are directly regulated by the biomass of active rhizosphere microorganisms.

Table 1. Essential Elements Required by Animals and Plants.

Major Essential Elements required by animals and plants

Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O)

Minor Essential Elements

Macronutrients required by animals and plants

Potassium (K), Calcium (Ca), Phosphorus (P), Magnesium (Mg), Sulfur (S)

Macronutrients required by animals

Sodium (Na), Chlorine (Cl)

Micronutrients required by animals and plants

Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu)

Molybdenum (Mo), Nickel (Ni)

Micronutrients required by animals

Iodine (I), Cobalt (Co), Selenium (Se), Chromium (Cr)

Micronutrients required by plants

Boron (B), Chlorine (Cl)

Blue elements required by both animals and plants, Red elements required by animals, Green elements required by plants.

The quantity of ecosystem biogeochemical processes conducted is also dependent on the quantity of rhizosphere microorganism biomass (Coleman et al. 1983). The greater the microbial biomass, the greater the grassland ecosystem productivity. The greater the productivity, the greater the annual increase in soil organic matter. Increases in the organic matter content of a soil improves the stability of soil aggregates, improves the physical and chemical properties, improves soil air and water infiltration and water holding capacity, improves soil fertility, and increases cation exchange capacity (Schimel, Coleman, and Horton 1985, Six et al. 1998, 2004).

The indispensable grass vegetation provides nutritious forage to large grazing graminivores. Grass plants use the major and minor essential elements in the inorganic form to synthesize vital organic components of carbohydrates, proteins, and nucleotides for growth. Grass plants have four primary internal plant growth mechanisms that help grass tillers withstand and recover from partial defoliation by grazing graminivores. The primary mechanisms are: compensatory physiological mechanisms (McNaughton 1979, 1983; Briske 1991); vegetative reproduction by tillering (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995); nutrient resource uptake (Crider 1955, Li and Wilson 1998, Kochy and Wilson 2000, Peltzer and Kochy 2001); and water use efficiency (Wight and Black 1972, 1979).

Compensatory physiological mechanisms give grass plants the capability to replace lost leaf and shoot biomass following partial grazing defoliation by increasing meristematic tissue activity, increasing photosynthetic capacity, and increasing allocation of carbon and nitrogen. Fully activated mechanisms can produce replacement foliage at 140% of the herbage weight that was removed during grazing (Manske 2000a, b, 2010a, b, 2014a, b). The growth rates of replacement leaves and shoots increase after partial defoliation by grazing. The enhanced activity of meristematic tissue produces larger leaves with greater mass (Langer 1972, Briske and Richards 1995). Developing leaf primordia not fully expanded at time of defoliation have increased growth rates and tend to grow larger than leaves on undefoliated tillers (Langer 1972). Partial defoliated tillers increase photosynthetic rates of remaining mature leaves and rejuvenated portions of older leaves not completely senescent (Atkinson 1986, Briske and Richards 1995). Changes in cytokinin levels and other signals produced as a result of the increase in the root-shoot ratio rejuvenate the photosynthetic apparatus, inhibit or reduce the rate of senescence, and increase the life span and leaf mass of remaining mature leaves (Briske and Richards 1995). Activation of the compensatory physiological mechanisms after partial defoliation of grass tillers by grazing require alternative sources of abundant carbon and nitrogen (Coyne et al. 1995). Carbon fixed during current photosynthesis in remaining mature leaf and shoot tissue and rejuvenated portions of older leaves is preferentially allocated to areas of active meristematic tissue (Ryle and Powell 1975, Richards and Caldwell 1985, Briske and Richards 1995, Coyne et al. 1995). The quantity of leaf area required to fix adequate quantities of carbon is 67% to 75% of the predefoliated leaf area (Manske 1999, 2011b, 2014c). Very little, if any, of the carbon and nitrogen stored in the root system is remobilized to support compensatory growth (Briske and Richards 1995). The mobilizable nitrogen pools in the shoot tissue are reduced following partial defoliation. This loss in nitrogen from the shoot increases preferential use of the quantities of mineral nitrogen available in the media around the roots (Millard et al. 1990, Ourry et al. 1990). This available soil mineral nitrogen has been converted from soil organic nitrogen by active rhizosphere organisms, absorbed though the roots, and moved to areas of active meristematic tissue.

Vegetative secondary tillers are shoots that develop on lead tillers from growth of axillary buds by the process of tillering (Dahl 1995). Meristematic activity in axillary buds and the subsequent development of vegetative tillers is regulated by auxin, a growth-inhibiting hormone produced in the apical meristem and young developing leaves (Briske and Richards 1995). Tiller growth from axillary buds is inhibited indirectly by auxin interference with the metabolic function of cytokinin, a growth hormone (Briske and Richrds 1995). Partial defoliation of young leaf material at vegetative growth stages temporarily reduces the production of the blockage hormone, auxin (Briske and Richards 1994). The abrupt reduction of plant auxin in the lead tiller allows for cytokinin synthesis or utilization in multiple axillary buds, stimulating the development of vegetative secondary tillers (Murphy and Briske 1992, Briske and Richards 1994). If no defoliation occurs before the flower (anthesis) stage, the lead tiller continues to hormonally inhibit secondary tiller development from axillary buds. Production of the inhibitory hormone, auxin, declines gradationally as the lead tiller reaches the flower stage. The natural reduction of auxin in the lead tiller usually permits only one secondary tiller to develop. This developing secondary tiller produces auxin that hormonally suppresses development of additional axillary buds (Briske and Richards 1995). Vegetative tiller growth is the dominant form of reproduction in semiarid and mesic grasslands (Belsky 1992, Chapman and Peat 1972, Briske and Richards 1995, Chapman 1996, Manske 1999) not sexual reproduction and the development of seedlings. Recruitment of new grass plants developed from seedlings is negligible in healthy grassland ecosystems. The frequency of true seedlings is extremely low in functioning grasslands, and establishment of seedlings occurs only during years with favorable moisture and temperature conditions (Wilson and Briske 1979, Briske and Richards 1995), in areas of reduced competition from vegetative tillers, and when resources are readily available to the growing seedling.

Grass plant dominance within a grassland community is related to the plants competitiveness at nutrient and water resource uptake. Crider (1955) found that grass tillers with 50% or more of the aboveground leaf material removed reduce root growth, root respiration, and root nutrient absorption resulting in reduced functionality of these grass plants. Reduction of active root biomass caused diminishment of grass plant health and vigor (Whitman 1974) that 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 contributed to the reduction of rhizosphere biomass and the decline of ecosystem biogeochemical processes (Coleman et al. 1983, Klein et al. 1988). The nutrient resource uptake competitiveness of healthy grasses is able to suppress the expansion of shrubs and prevent successful establishment of grass, forb, and shrub seedlings into grasslands (Peltzer and Kochy 2001). The grass growth form has competitive advantages of nutrient uptake over the shrub growth form (Kochy and Wilson 2000). Grass aboveground biomass is primarily productive photosynthetic leaves resulting in a high resource uptake efficiency. Grasses are good competitors for belowground nutrient resources and superior competitors for mineral nitrogen because of a high root: shoot ratio and no woody stems to maintain. Shrubs have a great reduction in resource uptake efficiency because a large portion of the photosynthates produced in the leaves must be used to build and maintain their unproductive woody stems. However, the taller woody stems make shrubs superior competitors for aboveground sunlight resources (Kochy and Wilson 2000). Competition for belowground nutrient resources from healthy grasses reduce the growth rates of shrub rhizomes and cause high mortality rates of young sucker (Li and Wilson 1998). Shrubs can compete for some of the belowground resources only after the grass plants have been degraded by ineffective management. Following the reduction in grass plant resource uptake competitiveness, the belowground resources no longer consumed by the smaller, less vigorous degraded grasses, are taken up by the shrub plants resulting in proportional increases of biomass production (Kochy and Wilson 2000). With greater nutrient resources, shrub rhizome suckers are able to establish a faster growth rate and a higher survival rate (Li and Wilson 1998). The resulting greater shrub stem density increases the competition for the aboveground resources of light causing strong suppression of the grasses (Kochy and Wilson 2000). Traditionally, the observation of increasing woody shrubs and trees into grasslands would have been explained as a result of fire suppression (Humphrey 1962, Stroddart, Smith, and Box 1975, Wright and Bailey 1982). The invasion of the cool season exotic grasses, Kentucky bluegrass, and smooth bromegrass, into much of the northern mixed grass prairie was presumed to be caused by the absence of fire (Kirsch and Kruse 1972). Seedlings of trees, shrubs, weedy forbs, and introduced grasses cannot become established in healthy functioning grassland ecosystems with grasses that have retained full resource uptake competitiveness (Peltzer and Kochy 2001).

Grasslands of the Northern Plains managed with traditional practices are notorious for their inhibitory deficiency in available soil mineral nitrogen (Goetz et al. 1978) which has been determined to cause the observed low herbage production. Deficiencies in mineral nitrogen limit herbage production more often than water deficiencies in temperate grasslands (Tilman 1990). Total herbage biomass production on grassland ecosystems has been shown to increase with increases in the quantity of available soil mineral nitrogen (Rogler and Lorenz 1957; Whitman 1957, 1963, 1976; Smika et al. 1965; Goetz 1969, 1975; Power and Alessi 1971; Lorenz and Rogler 1972; Taylor 1976; Wight and Black 1979). Greater quantities of available soil mineral nitrogen has been shown to also cause the soil water use efficiency to improve in grassland plants (Smika et al. 1965, Wight and Black 1972, Whitman 1976, 1978). Using a proxy method, Wight and Black (1972) found that precipitation (water) use efficiency of grass plants improved when soil mineral nitrogen was available at threshold quantities of 100 lbs/ac (112 kg/ha) and greater. The inhibitory deficiencies of mineral nitrogen on grasslands that had less than 100 lbs/ac of available soil mineral nitrogen caused the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the weight of herbage produced per inch of precipitation on the grassland ecosystem that had greater than 100 lbs/ac of mineral nitrogen and did not have mineral nitrogen deficiencies (Wight and Black 1979). The efficiency of water use in grass plants function at low levels when mineral nitrogen is deficient, and function at high levels when mineral nitrogen is available at threshold quantities of 100 lbs/ac or greater. The level of water use efficiency determines the level of herbage biomass productivity on grasslands. Manske (2010a, b) found that the threshold quantity of 100 lbs/ac of available mineral nitrogen was also critical for functionality for two internal grass plant growth mechanisms of the vegetative reproduction by tillering and the compensatory physiological mechanisms. Both of these mechanisms function at high potential levels on grasslands that have 100 lbs/ac or greater available soil mineral nitrogen and do not function or function at extremely low levels on grasslands that have mineral nitrogen deficiencies (Manske 2009c, 2010a, b, c, 2011c).

Production of herbage biomass on grassland ecosystems at potential biological levels requires mineral nitrogen to be available at the threshold amount of 100 lbs/ac or greater. The biogeochemical processes of the nitrogen cycle in grassland ecosystems that convert organic nitrogen into mineral nitrogen are a function of the complex symbiotic interactions among rhizosphere organisms, grass plants, and large grazing graminivores. Soil organic matter in grassland ecosystems generally contains about three to eight tons of organic nitrogen per acre. Organic nitrogen is a form of nitrogen not directly usable by grass plants. Organic nitrogen must be transformed into inorganic (mineral) nitrogen in order to be usable by plants. In grassland ecosystems, the transformation of plant usable mineral nitrogen from soil organic nitrogen requires active rhizosphere organisms comprised of several trophic levels of microbes existing in the narrow zone of soil around active roots of perennial grass plants (Harley and Smith 1983, Campbell and Greaves 1990, Caesar-TonThat et al. 2001b).

The nitrogen cycle within grassland soils functions with two major biogeochemical processes. Immobilization is the process of assimilation of mineral nitrogen into organic forms of living organisms. Mineralization is the process of converting organic nitrogen into mineral (inorganic) nitrogen. Mineralization is a complex biogeochemical process conducted by saprotrophic and heterotrophic soil microorganisms that convert immobilized organic nitrogen from soil organic matter detritus into mineral (inorganic) nitrogen (Power 1972). Ammonium salts are the first inorganic nitrogen compounds produced by microbial digestion. Complex proteins and other organic nitrogen compounds are simplified by enzymatic digestion that hydrolyze the peptide bonds and liberate and degrade the amino acids by deamination to produce ammonia (NH_3) and carbon dioxide, or other low molecular weight carbon compounds (Power 1972, Brady 1974). Most of the ammonia released is readily hydrolyzed into stable ammonium (NH_4). The ammonium ions are fairly immoble and some can be oxidized during nitrification producing nitrite (NO_2) and then nitrate (NO_3) (Brady 1974, Legg 1975, Coyne et al. 1975). The quantity of available nitrate in soil increases when the soil moisture content is abundant (Brady 1974). Mineral nitrogen (NH_4 and NO_3) have several optional biological and chemical pathways and are not available for very long. The quantity of available mineral nitrogen varies with changes in soil microorganism biomass and plant phenological growth and development during the growing season (Whitman 1975) and is the net difference between the total quantity of organic nitrogen mineralized by soil microorganisms and the quantity of mineral nitrogen immobilized into organic forms by plants and soil microbes (Brady 1974, Legg 1975). Maintaining available mineral nitrogen at the threshold quantity of 100 lbs/ac or greater requires a very large biomass of soil microorganisms.

Rhizosphere organism biomass and activity are limited by access to simple carbon chain energy (Curl and Truelove 1986) because the microflora trophic levels lack chlorophyll and have low carbon (energy) content. Partial defoliation by large indispensable grazing graminivores that removes 25% to 33% of the aboveground leaf and shoot weight from grass lead tillers in vegetative phenological growth between the three and a half new leaf stage and the flower stage (Manske 1999) causes large quantities of exudates containing simple carbon compounds to be released through the plant roots into the rhizosphere (Hamilton and Frank 2001). With the increase in availability of energy from simple carbon compounds in the rhizosphere, microorganism activity (Elliot 1978, Anderson et al. 1981, Whipps 1990) and biomass (Gorder, Manske, and Stroh 2004) greatly increase. The elevated biomass and activity of the microfauna trophic levels results in heavy grazing on the low carbon, high nitrogen content microflora trophic levels resulting in ingestion of greater quantities of nitrogen than the microfauna organisms need for a balanced diet based on energy (carbon); the excess nitrogen is excreted as ammonium (NH_4). As a result of the increase in availability of energy from the exudated simple carbon chains, the biomass and activity of rhizosphere organisms greatly increased, transforming greater quantities of organic nitrogen into 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).

The increased available mineral nitrogen is absorbed into grass plant roots and through complex processes, the plant combines the mineral nitrogen with carbon, hydrogen, and oxygen to synthesize different kinds of amino acids which are combined into large organic compounds to produce various types of proteins, nucleotides, and chlorophyll, resulting in greatly increased herbage biomass production at or near potential biological levels (Manske 1999, 2003). As a result of the great increase in ecosystem net primary productivity, much greater quantities of organic nitrogen are returned annually back to the grassland ecosystem pool of soil organic matter which will raise the ecosystem functionality. Without the stimulation from the partial defoliation of grass lead tillers by the indispensable grazing graminivores none of the ecosystem biogeochemical processes and the internal grass plant mechanisms are activated and do not function.

Management of grassland ecosystems without large grazing graminivores is not sustainable. Forty-five years of research have been devoted to the development of a biologically effective grazing management strategy that can improve and maintain grassland ecosystems at their potential biological levels.

Biologically Effective Management of Grassland Ecosystems

The biologically effective twice-over rotation strategy was designed to coordinate partial defoliation events with grass phenological growth stages, to meet the nutrient requirements of the grazing graminivores, the biological requirements of the grass plants and the rhizosphere microorganisms, to enhance the ecosystem biogeochemical processes, and to activate the internal grass plant growth mechanisms in order for grassland ecosystems to function at the greatest achievable levels.

The twice-over rotation grazing management strategy uses three to six native grassland pastures. Each pasture is grazed for two periods per growing season. The number of grazing periods is determined by the number of sets of tillers: one set of lead tillers and one set of vegetative secondary tillers per growing season. The first grazing period is 45 days long, ideally, from 1 June to 15 July, with each pasture grazed for 7 to 17 days (never less or more). The number of days of the first grazing period on each pasture is the same percentage of 45 days as the percentage of the total season's grazeable forage contributed by each pasture to the complete system. The forage is measured as animal unit months (AUM's). The average grazing season month is 30.5 days long (Manske 2012a). The number of days grazed are not counted by calendar dates but by the number of 24-hr periods grazed from the date and time the livestock are turned out to pasture. The second grazing period is 90 days long, ideally from 15 July to 14 October, each pasture is grazed for twice the number of days as in the first period. The length of the total grazing period is best at 135 days; 45 days during the first period plus 90 days during the second period. There is some flexibility in the grazing period dates. The starting date has a variance of plus or minus 3 days with a range of start dates from 29 May to 4 June. This gives an extreme early option to start on 29 May with the first period to 12 July and with the second period to 11 October. The extreme late alternative option can start on 4 June with the first period to 18 July and with the second period to 17 October. There is also the option to add a total of 2 days to the total length of the grazing period. These 2 days can be used when a scheduled rotation date occurs on an inconvenient date by adding one day to each of two rotation dates. The limit of additional days is two per year resulting in a total length of 137 days. If inconvenient rotation dates occur during 3 or more times, an equal number of days greater than two must be subtracted from the grazing season, so total number of days grazed per year does not exceed 137 days. If the start date is later than 4 June, the scheduled rotation dates must remain as if the start date were on 4 June, in order to maintain the coordinated match of the partial defoliation events with the grass phenological growth stages. The total number of days grazed will be 135 days minus the number of days from 4 June to the actual start date. However, it is best to start on 1 June each year.

During the first period, partial defoliation that removes 25% to 33% of the leaf biomass from grass lead tillers between the 3.5 new leaf stage and the flower stage increases the rhizosphere microbe biomass and activity, enhances the ecosystem biogeochemical processes, and activates the internal grass plant growth mechanisms. Manipulation of these processes and mechanisms does not occur at any other time during a growing season. During the second grazing period, the lead tillers are maturing and declining in nutritional quality and defoliation by grazing is only moderately beneficial to grass development. Adequate forage nutritional quality during the second period depends on the activation of sufficient quantities of vegetative secondary tillers from axillary buds during the first period. Livestock are removed from intact grassland pastures in mid October, towards the end of the perennial grass growing season, in order to allow the carryover tillers to store the carbohydrates and nutrients which will maintain plant mechanisms over the winter. Most of the upright vegetative tillers on grassland ecosystems during the autumn will be carryover tillers which will resume growth as lead tillers during the next growing season. Almost all grass tillers live for two growing seasons, the first season as vegetative secondary tillers and the second season as lead tillers. Grazing carryover tillers after mid October causes the termination of a large proportion of the population, resulting in greatly reduced herbage biomass production in subsequent growing seasons. The pasture grazed first in the rotation sequence is the last pasture grazed during the previous year. The last pasture grazed has the greatest live herbage weight on 1 June of the following season (Manske 2018a).

Stocking rates are based on peak herbage biomass on seasonlong grazing practices. The starting stocking rate on the "new" twice-over grazing practice is usually 80% to 100% of the seasonlong stocking rate. It usually requires three grazing seasons with the twice-over strategy stocked at 100% to increase the rhizosphere microbe biomass to be great enough to mineralize 100 lbs/ac of mineral nitrogen (nitrate NO_3 and ammonium NH_4). After the increased rhizosphere microbe biomass can mineralize 100 lbs/ac of mineral nitrogen, the stocking rate can be increased at 10% per year until the system is stocked at 140% of the seasonlong stocking rate. This has been the maximum biological potential reached on North American grasslands from the twice-over rotation strategy.

Once a rotation date scheduled has been determined, do not change that schedule greater than one day for any worldly reason. If you do not like your neighbors bull, build a fence that the bull cannot jump. If you have water sources that sometimes go dry, put in a water tank system on a pipeline. Fix the problems that develop with solutions that do not change the rotation schedule.

Grasslands of the Northern Plains managed by traditional practices are low in available mineral nitrogen. This low nitrogen availability has long been known to be responsible for the reduced herbage productivity and below genetic potential calf weight gains per acre perceived by grassland livestock producers. However, intact grasslands have adequate nitrogen, usually at 5 to 6 tons of organic nitrogen per acre, which is not available to plants. Organic nitrogen must be mineralized by soil microorganisms in order for it to be available for plant use in the inorganic form. Unfortunately, traditional and gimmick grazing management practices do not elevate the soil microorganism biomass high enough to support mineralization of organic nitrogen at a level that can yield a supply at the threshold quantity of 100 lbs/ac or greater (Wight and Black 1972, 1979), which will permit the four major grass plant growth mechanisms and all of the ecosystem biogeochemical processes to function at potential biological levels.

Changing traditional grazing management practices' rotation dates is not the first thing livestock producers think of when they realize they need to increase soil mineral nitrogen. Implementation of some quick fix agronomic practice is usually attempted first. The application of nitrogen fertilizer to grassland ecosystems does not solve the complex problems related to the cause of low soil mineral nitrogen (Manske 2014d). It was found that nitrogen fertilization of native grasslands caused a synchronization of grass tiller growth stage development, resulting in a small increase in herbage biomass which later produced a high rate of leaf senescence and an early season decrease in forage nutritional quality compared to nonfertilized grasslands (Manske 2014d). It also caused a short term shift in plant species composition, with an increase in mid cool season grass (e.g. western wheatgrass) and a decrease in short warm season grasses (e.g. blue grama) (Manske 2009a, 2014d). Initially, these changes were considered by most observers to be beneficial (Manske 2009d). However, close examination of the data showed that the costs of the additional herbage weight were excessive (Manske 2009b), and that the long term disruptions of ecosystem biogeochemical processes were detrimental to desirable plant composition (Manske 2010c). The reduction of short warm season grasses caused a decrease in total live plant basal cover, thus exposing greater amounts of soil to higher levels of solar radiation and erosion (Goetz et al. 1978). These large areas of open space became ideal invasion sites for undesirable plants, resulting in a long term plant species compositional shift towards a replacement community of domesticated and introduced mid cool season grasses (e.g. Kentucky bluegrass, Smooth bromegrass), and in the removal of nearly all the native plant species (Manske 2009c, 2010c, 2018a).

Implementation of the strategy to interseed alfalfa into intact semiarid native grassland does not solve the complex problems related to the cause of low soil mineral nitrogen (Manske 2005). The introduction of alfalfa increased demand on the existing low levels of soil mineral nitrogen because almost all of the alfalfa plants' nitrogen requirements had to be taken from the soil. The interseeded alfalfa plants had extremely low levels of nodulation of rhizobium bacteria on the roots and, consequently, almost no nitrogen fixation. The inoculated rhizobium had been consumed by the resident soil microbes before the alfalfa seedlings had grown sufficient root material to permit infection (Manske 2004). The low amounts of mineral nitrogen available in the soil resulted in slower rates of growth and higher rates of mortality for the interseeded alfalfa plants than those for alfalfa plants solid seeded into cropland (Manske 2005). In addition, the high water use of the interseeded alfalfa plants depleted soil water levels within a 5 foot radius from each crown to an average of 35% below ambient soil water levels, causing drought stress conditions in the adjacent grass plants and, subsequently, further reducing grass herbage production (Manske 2004, 2005). Agronomic strategies implemented on grassland ecosystems slowly stifled grass internal growth mechanisms and ecosystem biogeochemical processes to ineffectiveness (Manske 2018a).

Grassland ecosystems should be managed with sound ecological principles. The ecological method to increase the quantity of available mineral nitrogen to 100 lbs/ac or greater in grassland ecosystems is to increase the biomass of the rhizosphere microorganisms. The rhizosphere is the narrow zone of soil bonded by extra cellular adhesive polysaccharides around active roots of perennial grassland plants. The primary biologically active rhizosphere microbes are the endomycorrhizal fungi, ectomycorrhizal fungi, low carbon: high nitrogen bacteria, and normal carbon: nitrogen protozoa. The rhizosphere microbes do not possess chlorophyll nor do they have direct access to sunlight, as a consequence, these microbes are deficient of energy and require an outside source of simple carbon energy. Contrary to common assumptions, there isn't enough short chain carbon energy in recently dead grass material and there isn't enough energy from natural plant leakage to support a large active biomass of soil microbes. The only readily accessible source of large quantities of short chain carbon energy is the surplus fixed carbon energy photosynthesized by grass lead tillers at vegetative phenological growth stages. Grass plants fix a great deal more carbon energy than they use, furthermore, grass plants do not store the surplus fixed energy until during the winter hardening period, which starts in mid August and lasts to hard frost. Surplus carbon energy not programed for use, is broken down during night respiration. However, grass lead tillers at vegetative growth stages, between the three and a half new leaf stage and the flower (anthesis) stage, can be manipulated to exudate most of the surplus carbon energy into the rhizosphere through the roots following partial removal of 25% to 33% of the aboveground leaf biomass by grazing graminivores. This technique supplies sufficient quantities of short chain carbon energy into the rhizosphere initiating the production of large increases in microbe biomass and activity when 60% to 80% of the grass lead tiller population are partially defoliated by grazing graminivores over a period of 7 to 17 days on each pasture during the 45 day stimulation period from 1 June to 15 July.

Initiation of a twice-over strategy on native grassland that had previously been managed by nongrazing or traditional seasonlong practices will have a rhizosphere microbe biomass that is low to very low and it will require about three growing seasons to increase the microbe biomass large enough to mineralize 100 lbs/ac of mineral nitrogen. The response from the rhizosphere microbes is not instantaneous and rhizosphere weight changes respond differently to different management treatments. Annual changes in microbe weight on a nongrazed control treatment were small and appeared to be related to small changes in growing season precipitation during the first five years, with a relatively large change in microbe weight during the sixth year that corresponded with a substantial increase in growing season precipitation (table 2, figure 1). The rhizosphere weights on the twice-over managed pastures were not significantly different from those on the nongrazed control during the first two years. The microbe weights increased by 33% during the third year on the grazed pastures and continued to increase at a mean rate of 30.5 kg/m^3 per year from year 3 to 6, reaching a weight of 214.3 kg/m^3, which was 64.2% greater than the microbe weight on the nongrazed control (table 2, figure 1). After six years of management with the twice-over rotation strategy, 214 kg/m^3 of rhizosphere microbes were mineralizing 99.4 lbs/ac (111.3 kg/ha) of mineral nitrogen (Manske 2018c).

During treatment year 20, the effects from three management practices were evaluated monthly for changes in rhizosphere volume (Gorder, Manske, Stroh 2004). The management practices were nongrazed, seasonlong, and twice-over rotation. The rhizosphere volume changed little during the growing season months on the nongrazed and seasonlong treatments (table 3, figure 2). The test pasture of the twice-over system was the third pasture grazed. During the 14 day grazing period from 1 to 15 July, surplus carbon energy was exudated from partially defoliated lead tillers through the roots into the rhizosphere. The microbe biomass and rhizosphere volume increased and the biogeochemical processes that mineralize organic nitrogen into mineral nitrogen greatly increased. By the mid August sample period, the rhizosphere volume had increased 85.7% from the July volume (table 3, figure 2).

The relationship between microbe biomass, rhizosphere volume, and the quantity of available mineral nitrogen is not linear. As the grassland ecosystem aggrades and the quantity of herbage biomass increases, the biomass of rhizosphere microbes must also increase in order to mineralize the threshold quantity of mineral nitrogen at 100 lb/ac (112 kg/ha).

During treatment year 24, the largest rhizosphere biomass for the twice-over strategy was measured at 406.44 kg/m^3, which is now considered to be the Standard Reference Rhizosphere Weight. The apparent quantity of mineralized nitrogen was 176 kg/ha (157 lbs/ac). The twice-over rotation system is the only management strategy known to be able to maintain a large biomass of rhizosphere microbes that can mineralize nitrogen at or above the threshold quantity of 100 lbs/ac (112 kg/ha) (Manske 2018c).

Available mineral nitrogen at or above the threshold quantity of 100 lbs/ac permits grassland vegetation to be produced near the biological potential level. For thirty years, 1983 to 2012, the monthly herbage biomass data for standard biotype categories was collected by standard clipping methods on the silty ecological sites from the biologically effective concepts of twice-over management compared to the herbage biomass on the silty sites from the traditional concept of seasonlong management (Manske 2018b). In general, the mean monthly herbage biomass values for the cool and warm season grasses on the biologically effective concept were substantially greater than those on the traditional concept (tables 4 and 5, figures 3 and 4). The mean monthly herbage biomass values for the upland sedges and forbs on the biologically effective concept were lower than those on the traditional concept, except the mean herbage weight of upland sedge in October (tables 4 and 5, figures 3 and 4).

The cool season grasses on the biologically effective concept (table 4, figure 3) produced an impressively great lead tiller peak of 760.51 lbs/ac in July and then produced a greater secondary vegetative tiller peak of 826.89 lbs/ac in September. The secondary vegetative tillers were at growth stages greater than the three and a half new leaf stage and contained similar nutrient quality as the lead tillers had during the same growth stages. The cool season grasses on the traditional concept (table 5, figure 4) produced a 20.3% lower lead tiller peak of 606.10 lbs/ac in July and then produced a 33.6% lower secondary vegetative tiller peak of 548.70 lbs/ac in September.

The warm season grasses on the biologically effective concept (table 4, figure 3) produced a lead tiller peak at 333.21 lbs/ac in August which was 16.1% greater than the lead tiller peak of 287.08 lbs/ac produced in August on the traditional concept (table 5, figure 4) and then produced a secondary vegetative tiller herbage peak above 300 lbs/ac during September and October that was 29.9% greater than that on the traditional concept (tables 4 and 5, figure 3 and 4).

The herbage biomass production of upland sedge on the biologically effective concept was at a 12.4% lower mean weight than that produced on the traditional concept. The peak upland sedge biomass in July on the biologically effective concept was 204.99 lbs/ac (table 4, figure 3) which was 13.8% lower than the peak upland sedge biomass in July at 237.83 lbs/ac on the traditional concept (table 5, figure 4). During the initial stages after implementation of the biologically effective management concept, the upland sedge component greatly increased filling bare spaces in the plant community. The ecosystem continued to improve and develop. Around year 15, the cool and warm season grasses increased sufficiently to expand into the areas of upland sedge causing the upland sedges to decrease.

The herbage biomass production of forbs on the biologically effective concept was at a 28.6% lower mean weight than that produced on the traditional concept. The peak forb biomass in July on the biologically effective concept was 193.27 lbs/ac (table 4, figure 3) which was 34.2% lower than the peak forb biomass in July at 293.73 lbs/ac on the traditional concept (table 5, figure 4).

There is a huge biological advantage for grass plants to grow in an ecosystem in which the biogeochemical processes are performed by a large biomass of rhizosphere microbes functioning at potential levels and in which the four main grass plant growth mechanisms are functioning at biological levels with available quantities of mineral nitrogen at or above 100 lbs/ac and with adequate quantities of major and minor essential elements which are all made possible by the beneficial effects from the biologically effective twice-over rotation strategy. Greater quantities of live cool and warm season grasses with greater quantities of nutrients are available during the entire grazing period from 1 June to 15 October.

Grazing period dates must be coordinated with the grass plant herbage biomass production curves and the nutritional quality curves in order for cow and calf weight performance to be at genetic potential. The optimum coordinated dates for native grassland pastures in the Northern Plains is to graze from early June to mid October, ideally 1 June to 14 October. Cow and calf weight performance on the biologically effective concept of the twice-over rotation strategy were compared to those on the traditional concept of the seasonlong treatment. Pasture costs were determined using pasture rent value of $8.76 per acre and market value per pound of calf pasture accumulated live weight gain was determined from the low market value of $0.70 per pound, with both values occurring during 1993 and 1994 at the start of this sample period. The three native grassland pastures managed with the twice-over rotation strategy were stocked at 8 cows per 80 acres with 10.34 ac/AU and 2.30 ac/AUM. The one native grassland pasture managed with the seasonlong treatment was stocked at 7 cows per 80 acres with 11.69 ac/AU and 2.60 ac/AUM. Both treatments were replicated two times. The increased herbage biomass production permitted the greater stocking rate on the twice-over strategy (Manske 2018d).

The greater herbage biomass production and the improved herbage nutritional quality from mid July to mid October permitted greater cow and calf accumulated live weight performance of the biologically effective concept. On the twice-over system, calf weight gain was 380.47 lbs per head, 2.89 lbs per day, and 37.66 lbs per acre and cow weight gain was 86.92 lbs per head, 0.66 lbs per day, and 8.68 lbs per acre (table 6). On the seasonlong system, calf weight gain was 354.37 lbs per head, 2.65 lbs per day, and 30.61 lbs per acre and cow weight gain was 67.11 lbs per head, 0.50 lbs per day, and 5.91 lbs per acre (table 6). The cow and calf accumulated weight gain on the twice-over system was greater than those on the seasonlong system. Calf weight was 26.10 lbs per head greater, 0.24 lbs per day greater, and 7.05 lbs per acre greater and cow weight was 19.81 lbs per head greater, 0.16 lbs per day greater, and 2.77 lbs per acre greater (table 6). The dollar value captured was greater on the twice-over system than those on the seasonlong system. The pasture cost was $11.82 lower, calf pasture weight gain value was $15.16 greater, net return per cow-calf pair was $30.09 greater, and net return per acre was $4.37 greater (table 7).

On the seasonlong system managed with the traditional concept, cow daily weight gain decreased at an average of 47% per month from 1 June to 15 September (figure 5). Lead tillers of native cool season and warm season grasses decrease in crude protein content at an average rate of 24% and 23% per month, respectively, from 1 June to 15 September. The cow daily weight gain decreased 377% from 15 September to 15 October. The seasonlong cows lost weight the last month of the grazing period during 82% of the growing seasons. Calf daily weight gain averaged 2.79 lbs/day from 1 June to 15 September, then daily weight gain decreased to 2.11 lbs/day during the last month (figure 5). Cow weight accumulation occurred at about 28 lbs/month from 1 June to 15 September, then cows lost 26 lbs during the last month, which was more then 26% of their accumulated weight. Calf weight accumulation occurred at about 81 lbs/month during the entire grazing period (figure 6).

On the twice-over system managed with the biologically effective concept, cow daily weight gain decreased at an average of 34% during the first month (June), then the rate of daily weight gain increased each time the cows returned to pastures 1 and 2 for the second grazing period. A small increase in daily weight gain is assumed to occur for longer than 2 weeks when the cows returned to pasture 3 for the second grazing period, however, weight performance data was not collected during late season interim dates. The cows lost an average of 0.51 lbs/day during the first 2 weeks of October. This loss of cow weight occurred 36% of the time which experienced one month per growing season with severe water deficiency at 22% of LTM during August, September, or October resulting in an average cow weight loss of 1.93 lbs/day. During the other 64% of the growing seasons, the cow weight gain averaged 0.34 lbs/day during the first 2 weeks of October (figure 5). Calf daily weight gain averaged 3.08 lbs/day from 1 June to 15 September, then daily weight gains decreased to 2.28 lbs/day during the last month (figure 5). Cow weight accumulation occurred at about 32 lbs/month from 1 June to 15 September, then the cows lost an average of 17 lbs during the last month, which was about 15% of their accumulated weight. Calf weight accumulation occurred at about 88 lbs/month during the entire grazing period (figure 6).

Grazing native grassland for 4.5 months from 1 June to 15 October (137 days) is the ideal period for the best potential cow and calf weight performance to occur. Grazing earlier than 1 June, before the grass lead tillers produce 3.5 new leaves is extremely detrimental for grass herbage biomass production with reductions ranging between 20% and 45% losses that result in secondary problems from lost animal weight gains. Grazing later than 15 October when all native grasses are deficient of crude protein, cows lose weight and calf weight gains greatly decrease, and removing leaf biomass by grazing living carryover grass tillers causes great reductions in grass density and herbage biomass production during the following growing season.

The 45 day period from 1 June to 15 July is the only time that the internal grass plant growth mechanisms of compensatory physiological mechanisms, vegetative reproduction by tillering, nutrient resource uptake, and water use efficiency can be activated and the ecosystem biogeochemical processes performed by rhizosphere microorganisms can be enhanced by short chain carbon energy exudated from photosynthetic surpluses in grass lead tillers, through the roots into the rhizosphere and available to the microbes, resulting in increased activity that result in greater quantities of soil organic nitrogen to be mineralized providing mineral nitrogen at quantities at or greater than the threshold level of 100 lbs/ac. All of these mechanisms and processes require partial defoliation by grazing graminivores that removes 25% to 33% of the aboveground leaf material from grass lead tillers that are at phenological growth stages between the three and a half new leaf stage and the flower stage.

Prescribed fire and mowing grass hay cannot activate the grass plant growth mechanisms or the ecosystem biogeochemical processes because these practices remove too much of the leaf area preventing adequate quantities of carbon energy to be fixed through leaf photosynthesis. Stored carbohydrates are not mobilzed for compensatory replacement growth following defoliation events (Briske and Richards 1995).

Many grassland ecologists have retained the belief that grassland ecosystems can be managed with fire because they have accepted the observational concept that fire prevents the intrusion of shrubs and trees into grasslands (Weaver 1954, Humphrey 1962, Daubenmire 1974, Stoddart, Smith, and Box 1975, Wright and Bailey 1982). However, the presence of fire does not prove that grasslands need or are caused by fire (Heady 1975). The existence of a shrub component in a grassland is not a ecologically beneficial relationship as shrubs and grasses are adversarial inhibitive competitors. They compete for sunlight, mineral nitrogen, other essential elements, and soil water. Fire in grasslands cannot prevent the invasion of, or cause the removal of, shrubs and trees that are able to reproduce by vegetative secondary suckers (Wright and Bailey 1982; Manske 2006a, b). Almost all deciduous woody plants reproduce vegetatively, except big sagebrush (Artemisia tridentata) (Manske 2019). Seedlings of trees, shrubs, weedy forbs, and introduced grasses cannot become established in grasslands containing grasses with full nutrient resource uptake competitiveness (Peltzer and Kochy 2001). Intrusive seedlings can only be established after a grassland has been degraded by poor management practices.

Repeated prescribed fire can modify the composition of the aboveground vegetation in degraded grasslands which have been invaded by shrubs. The composition of introduced cool season grasses may change, and early succession and weedy forbs, and shrub aerial stems decrease temporarily after four repeated prescribed fires (Manske 2007a, 2011a). However, the fundamental problems of weak nutrient resource uptake, reduced water use efficiency, nonfunctional compensatory physiological mechanisms, impaired vegetative reproduction by tillering and diminished biogeochemical processes will remain in the degraded grassland ecosystem following repeated fire events. None of the biological, physiological, or asexual mechanisms within grass plants and none of the rhizosphere microbes or biogeochemical processes they perform are activated by fire (Manske 2007a, 2011a). Almost all of the essential elements in the aboveground herbage are volatilized when a grassland is burned, and if the soil is dry, some of the belowground essential elements are also lost (Russelle 1992). When the losses of essential elements are greater than the quantity of captured essential elements, the result is degradation of the grassland (McGill and Cole 1981). Fire does not improve grassland ecosystems biologically or ecologically and fire cannot replace the partial defoliation achieved by grazing graminivores in managing healthy and productive grassland ecosystems (Manske 2018a).

Often times, livestock grazing is removed to protect a grassland ecosystem based on naive presumptions that livestock grazing causes damage to grassland ecosystem. Livestock grazing is not what causes damage to grasslands; poor management of grazing livestock can cause serious damage to grasslands. The greatest antagonistic effects to grassland ecosystem occur from no livestock-idle land management concepts that rest grasslands from grazing defoliation. The term “rest” is a misnomer; resting a grassland does not cause revitalizations of crucial biological and ecological processes. Resting a grassland by withholding partial defoliation by grazing results in regression of ecosystem processes and biological growth mechanisms. Several negative changes occur relatively soon after grazing graminivores are removed from grasslands; the live root biomass of grasses decrease (Whitman 1974), standing dead leaves and litter accumulate (Brand and Goetz 1986), and ecosystem biogeochemical processes diminish (Manske 2011b).

The reduction of live root surface area causes a decrease in active root length for interaction with symbiotic rhizosphere organisms and causes a decrease in absorption of water and nutrients from the soil. Reduction of active root biomass and diminishment of grass plant health vigor result in a loss of resource uptake efficiency and a suppression of competitiveness of grass plants to take up mineral nitrogen, essential elements, and soil water (Kochy 1999, Kochy and Wilson 2000).

Grass plants produce double the quantity of leaf biomass than needed for normal plant growth and maintentance (Crider 1955, Coyne et al. 1995). Without grazing graminivores to remove the surplus herbage production, the standing leaf material accumulates rapidly and changes from an asset to a detriment. The accumulation of nondefoliated live and standing dead leaves of grasses reduce light penetration below native grass light saturation points (Peltzer and Kochy 2001). Native grasses have high light saturation points and require near full sunlight. Warm season grasses have higher light saturation points than cool season grasses (Kochy 1999, Kochy and Wilson 2000). Shading reduces native warm season grasses more than native cool season grasses. Introduced cool season domesticated grasses have lower light saturation points than native grasses, permitting domesticated grass to live in low light conditions. The accumulating standing dead leaves shade the lower leaves, increasing the rate of leaf senescence and reducing the rate of photosynthesis, causing a decrease in the supply of carbohydrates (Coyne et al. 1995) that results in a reduction in growth of leaves and roots (Langer 1972, Briske and Richards 1995). Grass leaves grown under shaded conditions become longer but narrower, thinner, and lower in weight (Langer 1972) than leaves in sunlight. Shaded grass plants shift to erect growth forms with a small number of tillers (Briske and Richards 1995). Lack of grazing reduces grass tiller densities by decreasing tiller development and increasing tiller mortality through shading (Manske 2013). After a few years, shading reduces the composition of native grass species in the ecosystem and increases the composition of shade-tolerant or shade-adapted replacement species, like smooth bromegrass and Kentucky bluegrass.

Standing dead material not in contact with soil does not decompose through microbial activity. Dead plant material on nongrazed treatments breaks down slowly over several years by leaching and weathering and builds up into a thick mulch layer. Thick mulch effectively blocks sunlight from reaching understory young grass leaves. Thick mulch modifies soil temperatures. 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 causing great reductions in grass growth of leaves and roots. 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 2000a, 2011a).

The loss of active root length is a contributing factor in the reduction of rhizosphere biomass. The primary cause for the reduction in rhizosphere biomass is, however, the great reduction in the quantity of carbohydrate energy exudated from the grass roots into the rhizosphere zone. Without partial defoliation by grazing, only a small quantity of short carbon chain energy leaks from the grass roots into the rhizosphere; this low amount of simple carbon compounds is barely enough to sustain a very small rhizosphere microbe biomass. A small biomass of rhizosphere organisms function at greatly reduced rates of organic material decomposition, and can mineralize only small quantities of nitrogen and other essential elements (Anderson et al. 1981, Coleman et al. 1983, Curl and Truelove 1986, Klein et al. 1988, Whipps 1990).

Grazing graminivores perform several indispensable functions for grassland ecosystems. Partial defoliation by grazing graminivores activate the four major internal grass plant growth mechanisms, enhance rhizosphere microorganisms activity and increase their biomass large enough to perform the ecosystem biogeochemical processes and to mineralize greater than 100 lbs/ac of mineral nitrogen plus the other essential elements, and they remove the surplus grass leaf biomass produced by grass plants before it can become a detriment to the ecosystem each growing season.

Grazing graminivores have difficulty in properly defoliating the grassland communities that grow on subirrigated soils. The grasses and sedges that grow below the switchgrass ring deposit silicate crystals in the leaf tissue. Because of the presence of these crystals in mature plants, graminivores consume only about 10% of the mature forage growing in these highly productive wet meadow communities. The ungrazed standing plant biomass restricts growth of young grass plants and this old material needs to be removed by mowing or burning periodically. The unpredictability of wet and dry conditions of subirrigated soils requires a flexible treatment schedule. A simple strategy would be to organize the wet meadow areas into three groups, with each group containing wet meadow areas from each of the grazed pastures, and all of the wet meadow areas in the same group would receive treatment during the same year. All of the wet meadows in each group would receive a mowing or burning treatment one time in a cycle of three to five years as conditions permit.

Grazing graminivores is biologically beneficial for grass plants and for grassland ecosystems when grazing periods are coordinated with grass phenological growth stages. The four primary physiological growth mechanisms within grass plants that perform the herbage replacement processes are activated with partial defoliation by grazing graminivores when 25% to 33% of leaf weight is removed from 60% to 80% of lead tillers during vegetative phenological growth stages between the three and a half new leaf and the flower stage when a threshold quantity of 100 lbs/ac of mineral nitrogen is available. Unavailable soil organic nitrogen must be mineralized by soil microbes in order for nitrogen to be usable by grass plants. A large biomass of rhizosphere microorganisms is required to mineralize a large quantity of nitrogen yielding 100 lbs/ac. Grassland microbes are achlorphyllous and cannot fix their own carbon energy. Large quantities of surplus short chain carbon energy are produced by healthy vegetative lead tillers that can be exudated into the microbial rhizosphere when 25% to 33% of the leaf weight is removed with partial defoliation by grazing graminivores while lead tillers are between the three and a half new leaf stage and the flower stage. The four primary physiological growth mechanisms are not functional when less than 100 lbs/ac of mineral nitrogen is available and are not activated when zero % or greater than 33% of the leaf weight of lead tillers is removed during vegetative growth stages.

Grazing graminivores receive nutritious forage from healthy grass plants. However, providing forage for graminivores is not the only purpose for grazing grasslands. Grass plants have biological requirements and have four primary physiological growth mechanisms that must be activated by partial defoliation by grazing. Rhizosphere microorganisms are needed in large quantities to perform all of the ecosystem biogeochemical processes, but are unable to fix carbon energy and require exudated short chain carbon energy that can be provided by partial defoliation by grazing. The three indispensable biotic components of grasslands; grass vegetation, rhizosphere organisms, and large graminivores; must have their biological requirements provided with partial defoliation by grazing graminivores in order for grassland ecosystems to function at achievable levels.

The successful sustainability of grassland ecosystems depends upon the implementation of biologically effective management strategies that can provide the biological and physiological requirements of the forage grass plants, soil microorganisms, and grazing graminivores, that can activate and maintain the grass plant growth mechanisms and the ecosystem biogeochemical processes, that can revitalize soil structure and functionality, that can increase forage growth and nutritional quality, and that can improve livestock growth and weight performance along with the capture of greater wealth per acre.

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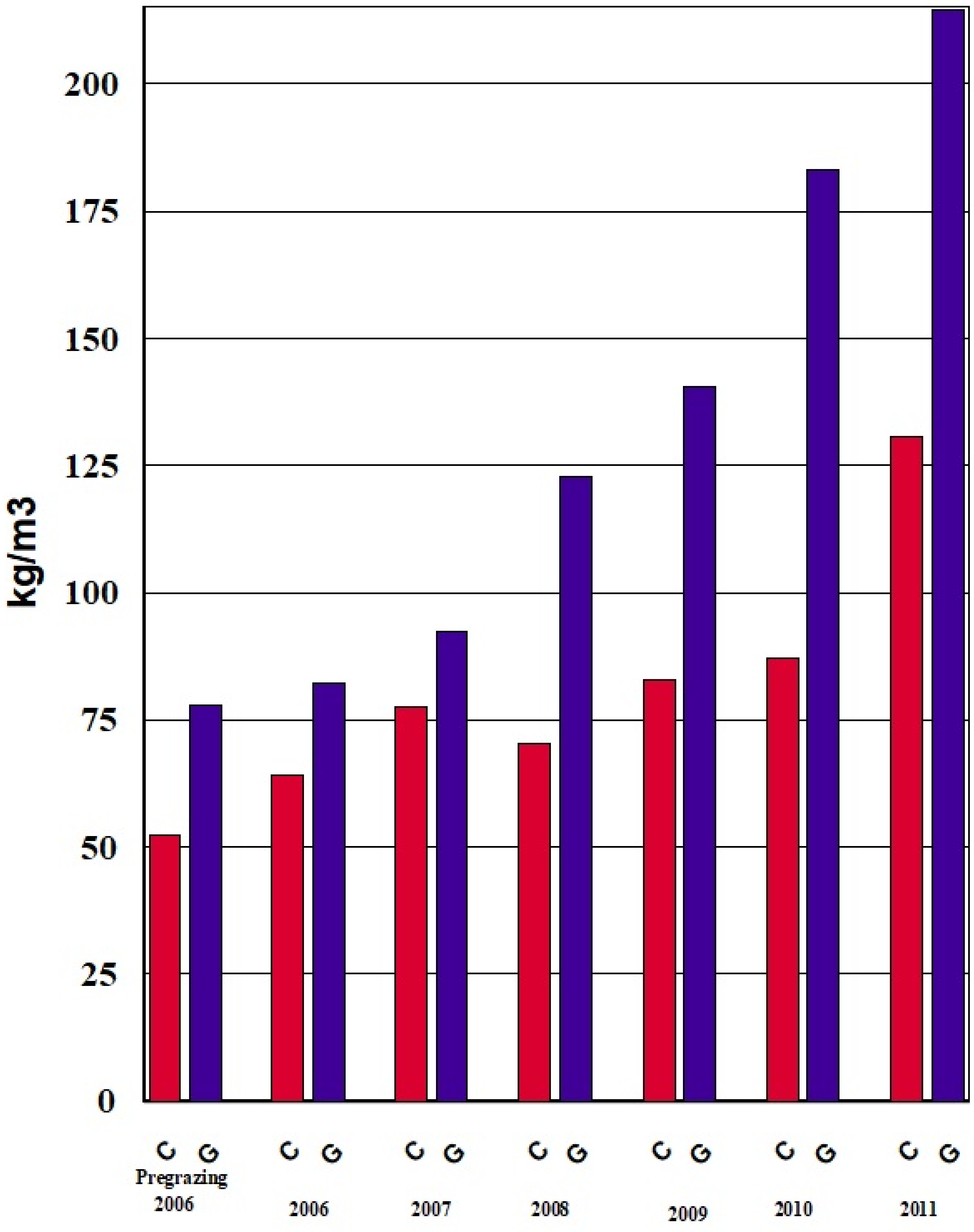

Figure 1. Rhizosphere weight (kg/m3) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Table 2. Rhizosphere weight (kg/m^3) for the nongrazed 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 ($P<0.05$).

Table 3. Rhizosphere volume in cubic centimeters per cubic meter of soil (cm^3/m^3), 2002, year 20.

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.

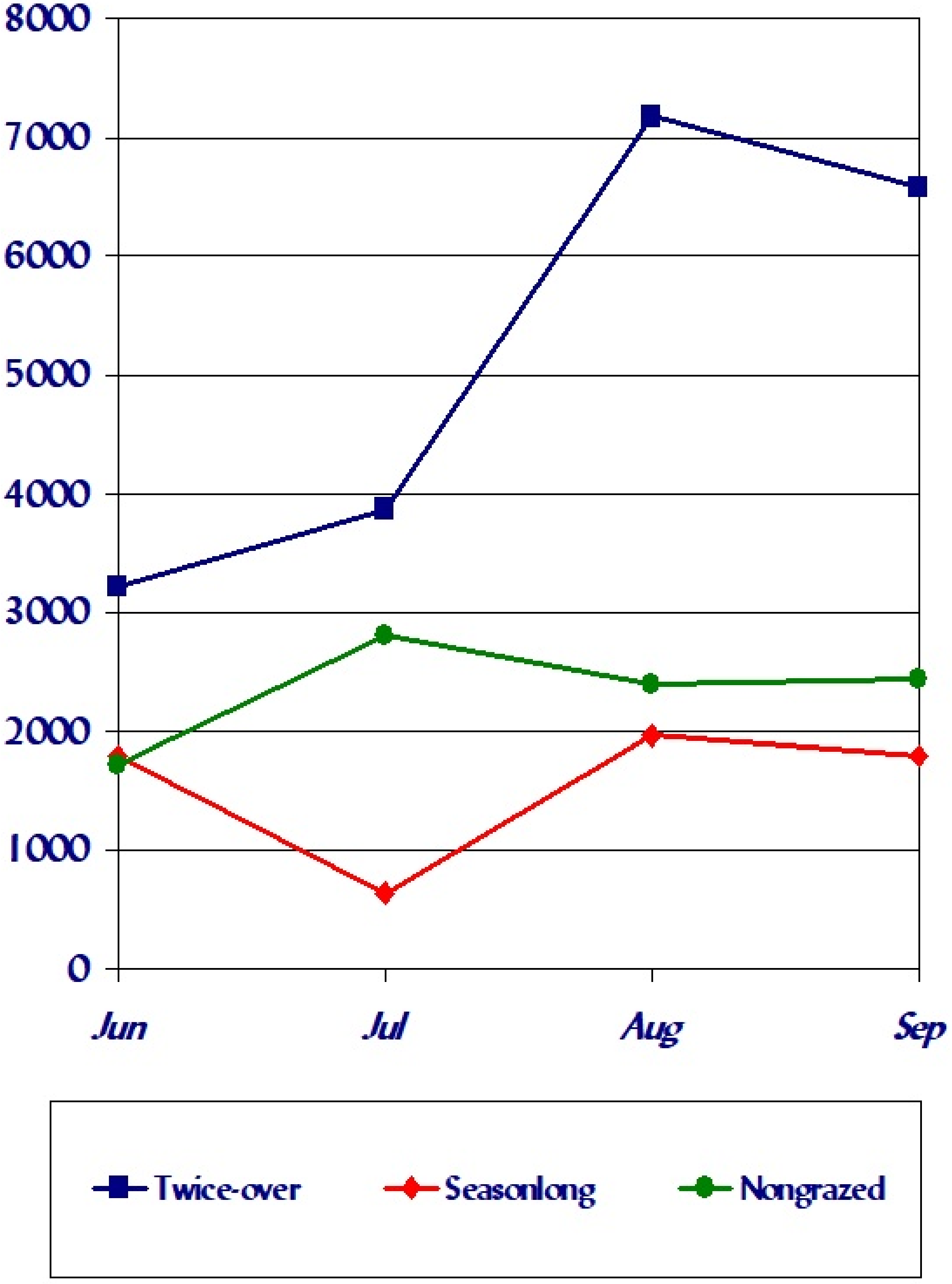

Figure 2. Rhizosphere volume (cm^3) per cubic meter of soil

Table 4. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Biologically Effective concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	397.73	637.66	760.51	670.20	826.89	698.80
Warm Season	179.90	217.06	304.43	333.21	300.86	302.53
Upland Sedge	165.99	199.29	204.99	175.74	127.28	137.21
Forbs	145.26	146.55	193.27	187.79	164.72	159.88
Grasses	577.63	854.72	1064.94	1003.41	1127.75	1001.33
Graminoids	743.62	1054.01	1269.93	1179.15	1255.03	1138.54
Total	888.88	1200.56	1463.20	1366.94	1419.75	1298.42

Table 5. Mean monthly herbage biomass (lbs/ac) by biotype categories on the silty ecological sites of the Traditional concept, 1983-2012.

Silty Site	May	Jun	Jul	Aug	Sep	Oct
Cool Season	308.46	483.96	606.10	515.39	548.70	542.12
Warm Season	123.98	157.64	244.45	287.08	222.68	241.69
Upland Sedge	168.26	226.16	237.83	222.50	151.45	126.55
Forbs	166.47	218.24	293.73	253.01	212.18	216.13
Grasses	432.44	641.60	850.55	802.47	771.38	783.81
Graminoids	600.70	867.76	1088.38	1024.97	922.83	910.36
Total	767.17	1086.00	1382.11	1277.98	1135.01	1126.49

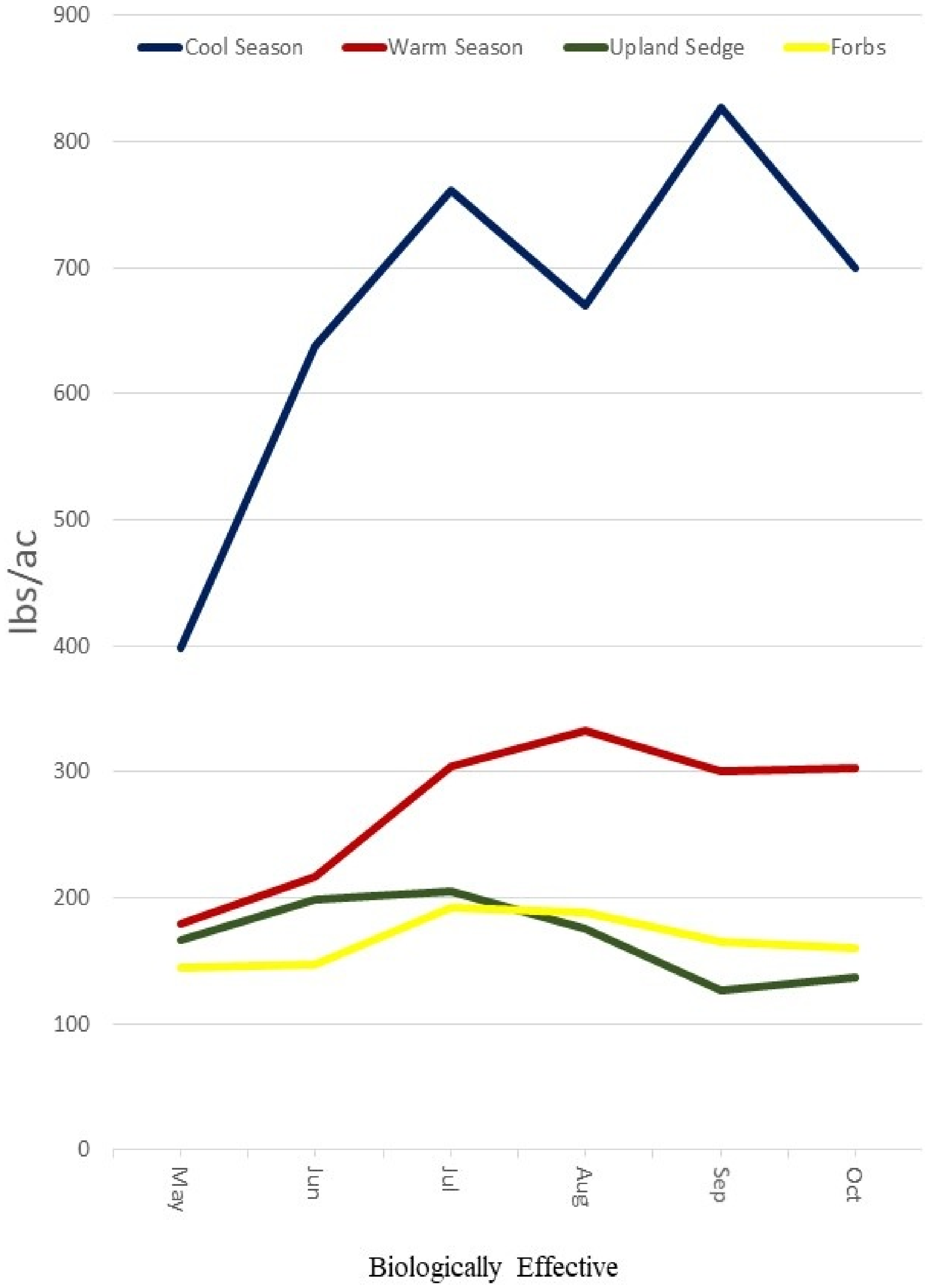

Figure 3. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Biologically Effective concept, 1983-2012.

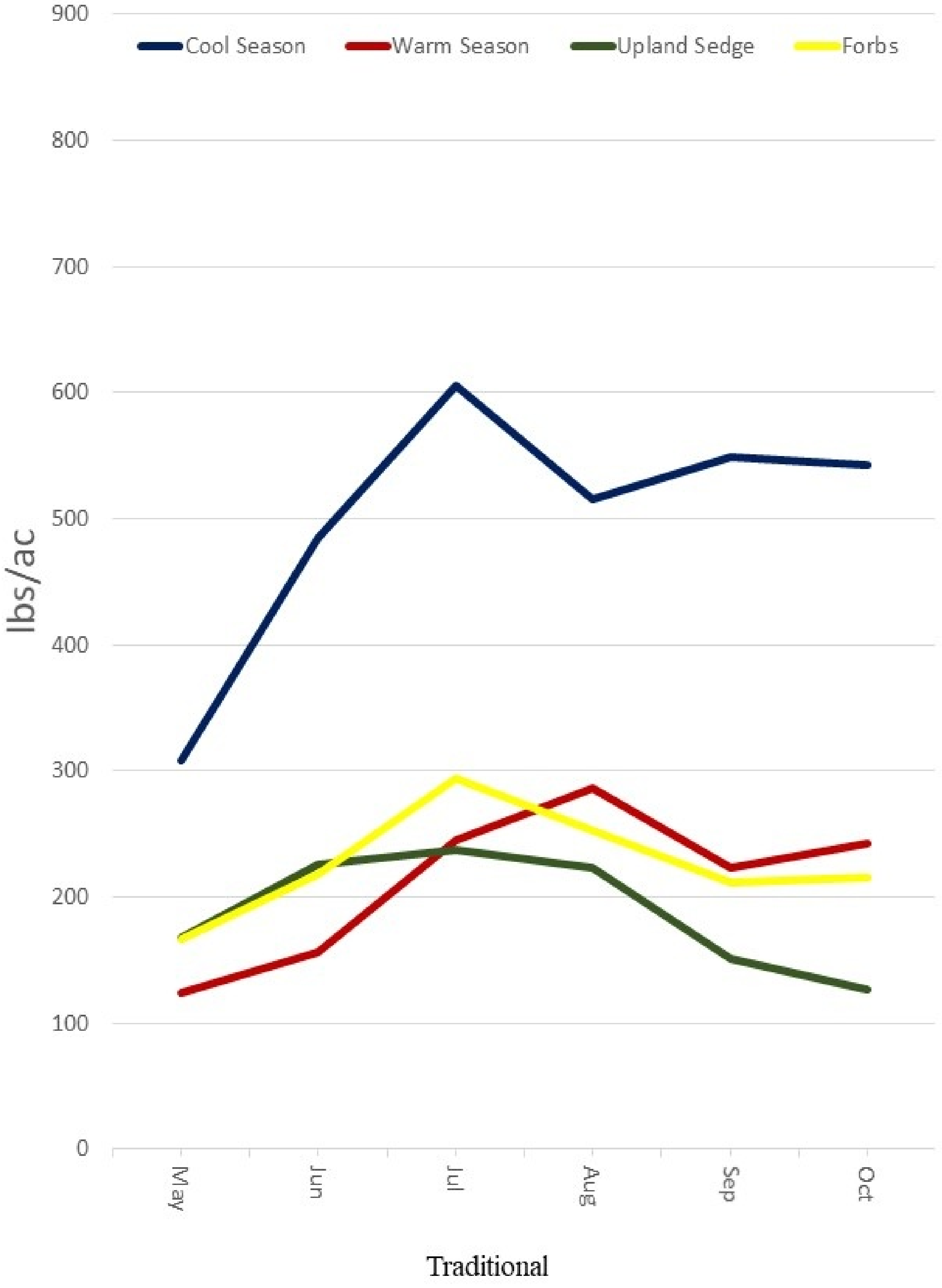

Figure 4. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Traditional concept, 1983-2012.

Table 6. Cow and calf weight performance grazing summer native rangeland pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept			Biologically Effective Concept			Biological Gain		
Native Rangeland	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs	Wt Gain lbs	Gain per Day lbs	Gain per Acre lbs
1995-2005	One Pasture, 11.69 ac/AU Seasonlong			Three Pastures, 10.34 ac/AU Twice-over rotation					
Calf	354.37	2.65	30.61	380.47	2.89	37.66	26.10	0.24	7.05
Cow	67.11	0.50	5.91	86.92	0.66	8.68	19.81	0.16	2.77

Table 7. Value captured gain in dollars from summer native rangeland pastures managed by the biologically effective concept compared to pastures managed by the traditional concept.

	Traditional Concept				Biologically Effective Concept				Value Captured Gain			
Native Rangeland	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $	Pasture Cost $	Pasture Weight Gain Value $	Net Return per C-C pr $	Net Return per Acre $
1995-2005	One Pasture, 11.69 ac/AU Seasonlong				Three Pastures, 10.34 ac/AU Twice-over rotation							
Cow-Calf pair	102.42	248.06	145.64	12.67	90.60	263.22	175.73	17.04	-11.82	15.16	30.09	4.37

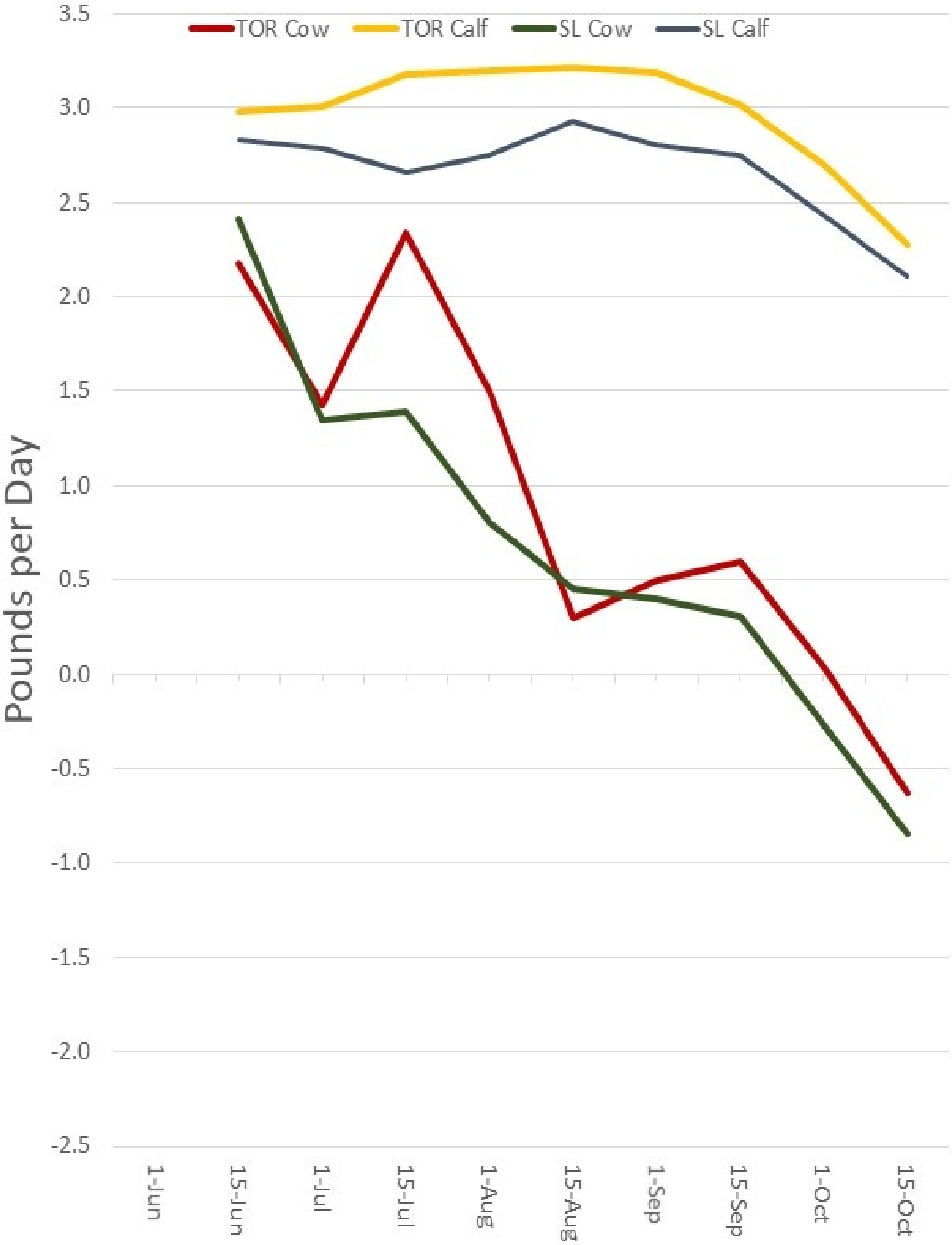

Figure 5. Cow and calf daily gain on the seasonlong and twice-over grazing systems, 1995-2005.

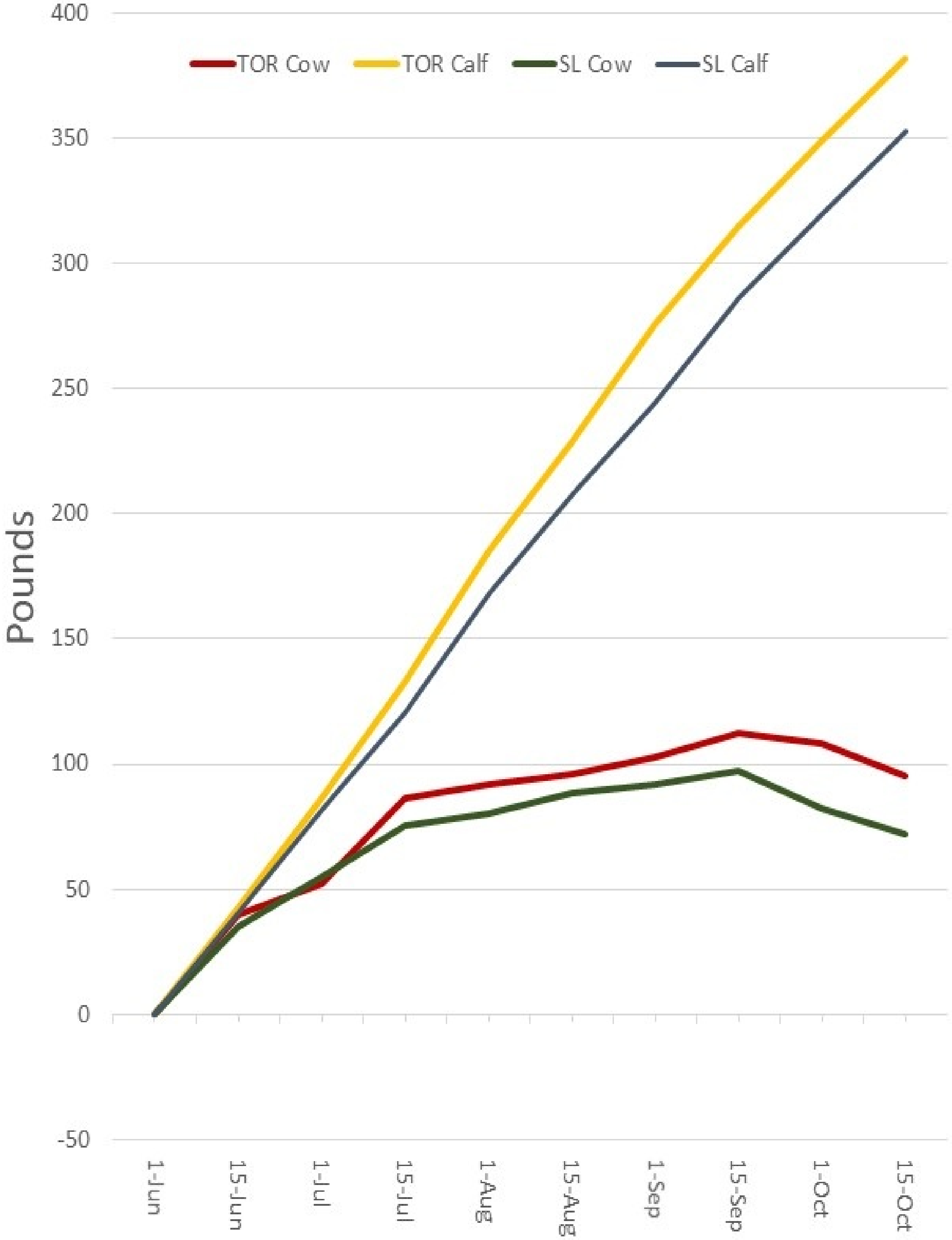

Figure 6. Cow and calf accumulated weight gain on the seasonlong and twice-over grazing systems, 1995-2005.

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Range Plant Growth Related to Climatic Factors of Western North Dakota, 1982-2019.

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Introduction

Successful long-term management of grassland ecosystems requires knowledge of the relationships of range plant growth and regional climatic factors. Range plant growth and development are regulated by climatic conditions. Length of daylight, temperature, precipitation, and water deficiency are the most important climatic factors that affect rangeland plants (Manske 2011).

Light

Light is necessary for plant growth because light is the source of energy for photosynthesis. Plant growth is affected by variations in quality, intensity, and duration of light. The quality of light (wavelength) varies from region to region, but the quality of sunlight does not vary enough in a given region to have an important differential effect on the rate of photosynthesis. However, the intensity (measurable energy) and duration (length of day) of sunlight change with the seasons and affect plant growth. Light intensity varies greatly with the season and with the time of day because of changes in the angle of incidence of the sun's rays and the distance light travels through the atmosphere. Light intensity also varies with the amount of humidity and cloud cover because atmospheric moisture absorbs and scatters light rays.

The greatest variation in intensity of light received by range plants results from the various degrees of shading from other plants. Most range plants require full sunlight or very high levels of sunlight for best growth. Shading from other plants reduces the intensity of light that reaches the lower leaves of an individual plant. Grass leaves grown under shaded conditions become longer but narrower, thinner (Langer 1972, Weier et al. 1974), and lower in weight than leaves in sunlight (Langer 1972). Shaded leaves have a reduced rate of photosynthesis, which decreases the carbohydrate supply and causes a reduction in growth rate of leaves and roots (Langer 1972). Shading increases the rate of senescence in lower, older leaves. Accumulation of standing dead leaves ties up carbon and nitrogen. Decomposition of leaf material through microbial activity can take place only after the leaves have made contact with the soil. Standing dead material not in contact with the soil does not decompose but breaks down slowly as a result of leaching and weathering. Under ungrazed treatments the dead leaves remain standing for several years, slowing nutrient cycles, restricting nutrient supply, and reducing soil microorganism activity in the top 12 inches of soil. Standing dead leaves shade early leaf growth in spring and therefore slow the rate of growth and reduce leaf area. Long-term effects of shading, such as that occurring in ungrazed grasslands and under shrubs or leafy spurge, reduce the native grass species composition and increase composition of shade-tolerant or shade-adapted replacement species like smooth bromegrass and Kentucky bluegrass.

Day-length period (photoperiod) is one of the most dependable cues by which plants time their activities in temperate zones. Day-length period for a given date and locality remains the same from year to year. Changes in the photoperiod function as the timer or trigger that activates or stops physiological processes bringing about growth and flowering of plants and that starts the process of hardening for resistance to low temperatures in fall and winter. Sensory receptors, specially pigmented areas in the buds or leaves of a plant, detect day length and night length and can activate one or more hormone and enzyme systems that bring about physiological responses (Odum 1971, Daubenmire 1974, Barbour et al. 1987).

The phenological development of rangeland plants is triggered by changes in the length of daylight. Vegetative growth is triggered by photoperiod and temperature (Langer 1972, Dahl 1995), and reproductive initiation is triggered primarily by photoperiod (Roberts 1939, Langer 1972, Leopold and Kriedemann 1975, Dahl 1995) but can be slightly modified by temperature and precipitation (McMillan 1957, Leopold and Kriedemann 1975, Dahl and Hyder 1977, Dahl 1995). Some plants are long-day plants and others are short-day plants. Long-day plants reach the flower phenological stage after exposure to a critical photoperiod and during the period of increasing daylight between mid April and mid June. Generally, most cool-season plants with the C_3 photosynthetic pathway are long-day plants and reach flower phenophase before 21 June. Short-day plants are induced into flowering by day lengths that are shorter than a critical length and that occur during the period of decreasing day length after mid June. Short-day plants are technically responding to the increase in the length of the night period rather than to the decrease in the day length (Weier et al. 1974, Leopold and Kriedemann 1975). Generally, most warm-season plants with the C_4 photosynthetic pathway are short-day plants and reach flower phenophase after 21 June.

The annual pattern in the change in daylight duration follows the seasons and is the same every year for each region. Grassland management strategies based on phenological growth stages of the major grasses can be planned by calendar date after the relationships between phenological stage of growth of the major grasses and time of season have been determined for a region.

Temperature

Temperature is an approximate measurement of the heat energy available from solar radiation. At both low and high levels temperature limits plant growth. Most plant biological activity and growth occur within only a narrow range of temperatures, between 32º F (0° C) and 122º F (50º C) (Coyne et al. 1995). Low temperatures limit biological reactions because water becomes unavailable when it is frozen and because levels of available energy are inadequate. However, respiration and photosynthesis can continue slowly at temperatures well below 32º F if plants are "hardened". High temperatures limit biological reactions because the complex structures of proteins are disrupted or denatured.

Periods with temperatures within the range for optimum plant growth are very limited in western North Dakota. The frost-free period is the number of days between the last day with minimum temperatures below 32º F (0º C) in the spring and the first day with minimum temperatures below 32º F (0º C) in the fall and is approximately the length of the growing season for annually seeded plants. The frost-free period for western North Dakota generally lasts for 120 to 130 days, from mid to late May to mid to late September (Ramirez 1972). Perennial grassland plants are capable of growing for periods longer than the frost-free period, but to continue active growth they require temperatures above the level that freezes water in plant tissue and soil. Many perennial plants begin active growth more than 30 days before the last frost in spring and continue growth after the first frost in fall. The growing season for perennial plants is considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with mean daily temperature at or above 32º F (0º C). In western North Dakota the growing season for perennial plants is considered to be generally from mid April through mid October. Low air temperature during the early and late portions of the growing season greatly limits plant growth rate. High temperatures, high evaporation rates, drying winds, and low precipitation levels after mid summer also limit plant growth.

Different plant species have different optimum temperature ranges. Cool-season plants, which are C_3 photosynthetic pathway plants, have an optimum temperature range of 50° to 77°F (10° to 25°C). Warm-season plants, which are C_4 photosynthetic pathway plants, have an optimum temperature range of 86° to 105°F (30° to 40°C) (Coyne et al. 1995).

Water (Precipitation)

Water, an integral part of living systems, is ecologically important because it is a major force in shaping climatic patterns and biochemically important because it is a necessary component in physiological processes (Brown 1995). Water is the principal constituent of plant cells, usually composing over 80% of the fresh weight of herbaceous plants. Water is the primary solvent in physiological processes by which gases, minerals, and other materials enter plant cells and by which these materials are translocated to various parts of the plant. Water is the substance in which processes such as photosynthesis and other biochemical reactions occur and a structural component of proteins and nucleic acids. Water is also essential for the maintenance of the rigidity of plant tissue and for cell enlargement and growth in plants (Brown 1977, Brown 1995).

Water Deficiency

Temperature and precipitation act together to affect the physiological and ecological status of range plants. The biological situation of a plant at any time is determined by the balance between rainfall and potential evapotranspiration. The higher the temperature, the greater the rate of evapotranspiration and the greater the need for rainfall to maintain homeostasis. When the amount of rainfall received is less than potential evapotranspiration demand, a water deficiency exists. Evapotranspiration demand is greater than precipitation in the mixed grass and short grass prairie regions. The tall grass prairie region has greater precipitation than evapotranspiration demand. Under water deficiency conditions, plants are unable to absorb adequate water to match the transpiration rate, and plant water stress develops. Range plants have mechanisms that help reduce the damage from water stress, but some degree of reduction in herbage production occurs.

Plant water stress limits growth. Plant water stress develops in plant tissue when the rate of water loss through transpiration exceeds the rate of water absorption by the roots. Water stress can vary in degree from a small decrease in water potential, as in midday wilting on warm, clear days, to the lethal limit of desiccation (Brown 1995).

Early stages of water stress slow shoot and leaf growth. Leaves show signs of wilting, folding, and discoloration. Tillering and new shoot development decrease. Root production may increase. Senescence of older leaves accelerates. Rates of cell wall formation, cell division, and protein synthesis decrease. As water stress increases, enzyme activity declines and the formation of necessary compounds slows or ceases. The stomata begin to close; this reaction results in decreased rates of transpiration and photosynthesis. Rates of respiration and translocation decrease substantially with increases in water stress. When water stress becomes severe, most functions nearly or completely cease and serious damage occurs. Leaf and root mortality induced by water stress progresses from the tips to the crown. The rate of leaf and root mortality increases with increasing stress. Water stress can increase to a point that is lethal, resulting in damage from which the plant cannot recover. Plant death occurs when meristems become so dehydrated that cells cannot maintain cell turgidity and biochemical activity (Brown 1995).

Study Area

The study area is the region around the Dickinson Research Extension Center (DREC) Ranch, Dunn County, western North Dakota, USA. Native vegetation in western North Dakota is the Wheatgrass-Needlegrass Type (Barker and Whitman 1988, Shiflet 1994) of the mixed grass prairie.

The climate of western North Dakota has changed several times during geologic history (Manske 1999). The most recent climate change occurred about 5,000 years ago, to conditions like those of the present, with cycles of wet and dry periods. The wet periods have been cool and humid, with greater amounts of precipitation. A brief wet period occurred around 4,500 years ago. Relatively long periods of wet conditions occurred in the periods between 2,500 and 1,800 years ago and between 1,000 and 700 years ago. Recent short wet periods occurred in the years from 1905 to 1916, 1939 to 1947, and 1962 to 1978. The dry periods have been warmer, with reduced precipitation and recurrent summer droughts. A widespread, long drought period occurred between the years 1270 and 1299, an extremely severe drought occurred from 1863 through 1875, and other more recent drought periods occurred from 1895 to 1902, 1933 to 1938, and 1987 to 1992. The current climatic pattern in western North Dakota is cyclical between wet and dry periods and has existed for the past 5,000 years (Bluemle 1977, Bluemle 1991, Manske 1994a).

Procedures

Daylight duration data for the Dickinson location of latitude 46° 48' N, longitude 102° 48' W, were tabulated from daily sunrise and sunset time tables compiled by the National Weather Service, Bismarck, North Dakota.

Temperature and precipitation data were taken from historical climatological data collected at the Dickinson Research Extension Center Ranch, latitude 47° 14' N, longitude 102° 50' W, Dunn County, near Manning, North Dakota, 1982-2019.

A technique reported by Emberger et al. (1963) was used to develop water deficiency months data from historical temperature and precipitation data. The water deficiency months data were used to identify months with conditions unfavorable for plant growth. This method plots mean monthly temperature (° C) and monthly precipitation (mm) on the same axis, with the scale of the precipitation data at twice that of the temperature data. The temperature and precipitation data are plotted against an axis of time. The resulting ombrothermic diagram shows general monthly trends and identifies months with conditions unfavorable for plant growth. Water deficiency conditions exist during months when the precipitation data bar drops below the temperature data curve and plants are under water stress. Plants are under temperature stress when the temperature curve drops below the freezing mark (0° C).

Results and Discussion

Light

The tilt of the earth's axis in conjunction with the earth's annual revolution around the sun produces the seasons and changes the length of daylight in temperate zones. Dickinson (figure 1) has nearly uniform day and night lengths (12 hours) during only a few days, near the vernal and autumnal equinoxes, 20 March and 22 September, respectively, when the sun's apparent path crosses the equator as the sun travels north or south, respectively. The shortest day length (8 hours, 23 minutes) occurs at winter solstice, 21 December, when the sun's apparent path is farthest south of the equator. The longest day length (15 hours, 52 minutes) occurs at summer solstice, 21 June, when the sun's apparent path is farthest north of the equator. The length of daylight during the growing season (mid April to mid October) oscillates from about 13 hours in mid April, increasing to nearly 16 hours in mid June, then decreasing to around 11 hours in mid October (figure 1).

Temperature

The DREC Ranch in western North Dakota experiences severe, windy, dry winters with little snow accumulation. The springs are relatively moist in most years, and the summers are often droughty but are interrupted periodically by thunderstorms. The long-term (38-year) mean annual temperature is 42.1° F (5.7° C) (table 1). January is the coldest month, with a mean temperature of 14.7° F (-9.6° C). July and August are the warmest months, with mean temperatures of 69.7° F (20.9° C) and 68.4° F (20.2° C), respectively. Months with mean monthly temperatures below 32.0° F (0.0° C) are too cold for active plant growth. Low temperatures define the growing season for perennial plants, which is generally from mid April to mid October (6.0 months, 183 days). During the other 6 months each year, plants in western North Dakota cannot conduct active plant growth. Soils are frozen to a depth of 3 to 5 feet for a period of 4 months (121 days) (Larson et al. 1968). The early and late portions of the 6-month growing season have very limited plant activity and growth. The period of active plant growth is generally 5.5 months (168 days).

Western North Dakota has large annual and diurnal changes in monthly and daily air temperatures. The range of seasonal variation of average monthly temperatures between the coldest and warmest months is 55.0° F (30.5° C), and temperature extremes in western North Dakota have a range of 161.0° F (89.4° C), from the highest recorded summer temperature of 114.0° F (45.6° C) to the lowest recorded winter temperature of -47.0° F (-43.9° C). The diurnal temperature change is the difference between the minimum and maximum temperatures observed over a 24-hour period. The average diurnal temperature change during winter is 22.0° F (12.2° C), and the change during summer is 30.0° F (16.7° C). The average annual diurnal change in temperature is 26.0° F (14.4° C) (Jensen 1972). The large diurnal change in temperature during the growing season, which has warm days and cool nights, is beneficial for plant growth because of the effect on the photosynthetic process and respiration rates (Leopold and Kriedemann 1975).

Precipitation

The long-term (38-year) annual precipitation for the Dickinson Research Extension Center Ranch in western North Dakota is 17.27 inches (438.61 mm). The long-term mean monthly precipitation is shown in table 1. The growing-season precipitation (April to October) is 14.60 inches (370.79 mm) and is 84.54% of annual precipitation. June has the greatest monthly precipitation, at 3.20 inches (81.38 mm).

The seasonal distribution of precipitation (table 2) shows the greatest amount of precipitation occurring in the spring (7.24 inches, 41.94%) and the least amount occurring in winter (1.64 inches, 9.49%). Total precipitation received for the 5-month period of November through March averages less than 2.66 inches (15.40%). The precipitation received in the 3-month period of May, June, and July accounts for 47.13% of the annual precipitation (8.14 inches).

The annual and growing-season precipitation levels and percent of the long-term mean for 38 years (1982 to 2019) are shown in table 3. Drought conditions exist when precipitation amounts for a month, growing season, or annual period are 75% or less of the long-term mean. Wet conditions exist when precipitation amounts for a month, growing season, or annual period are 125% or greater of the long-term mean. Normal conditions exist when precipitation amounts for a month, growing season, or annual period are greater than 75% and less than 125% of the long-term mean. Between 1982-2019, 5 drought years (13.16%) (table 4) and 6 wet years (15.79%) (table 5) occurred. Annual precipitation amounts at normal levels, occurred during 27 years (71.05%) (table 3). The area experienced 5 drought growing seasons (13.16%) (table 6) and 7 wet growing seasons (18.42%) (table 7). Growing-season precipitation amounts at normal levels occurred during 26 years (68.42%) (table 3). The 6-year period (1987-1992) was a long period with near-drought conditions. The average annual precipitation for these 6 years was 12.12 inches (307.89 mm), only 70.18% of the long-term mean. The average growing-season precipitation for the 6-year period was 9.97 inches (253.11 mm), only 68.29% of the long-term mean (table 3).

Water Deficiency

Monthly periods with water deficiency conditions are identified on the annual ombrothermic graphs when the precipitation data bar drops below the temperature data curve. On the ombrothermic graphs, periods during which plants are under low-temperature stress are indicated when the temperature curve drops below the freezing mark of 0.0º C (32.0º F). The long-term ombrothermic graph for the DREC Ranch (figure 2) shows that near water deficiency conditions exist for August, September, and October. This finding indicates that range plants generally may have a difficult time growing and accumulating herbage biomass during these 3 months. Favorable water relations occur during May, June, and July, a condition indicating that range plants should be able to grow and accumulate herbage biomass during these 3 months.

The ombrothermic relationships for the Dickinson Research Extension Center Ranch in western North Dakota are shown for each month in table 8. The 38-year period (1982 to 2019) had a total of 228 months during the growing season. Of these growing-season months, 67.0 months had water deficiency conditions, which indicates that range plants were under water stress during 29.3% of the growing-season months (tables 8 and 9): this amounts to an average of 2.0 months during every 6.0-month growing season range plants have been limited in growth and herbage biomass accumulation because of water stress. The converse indicates that only 4.0 months of an average year have conditions in which plants can grow without water stress.

Most growing seasons have months with water deficiency conditions. In only 5 of the 38 years (table 8) did water deficiency conditions not occur in any of the six growing-season months. In each growing-season month of 1982, 2013, 2015, 2016, and 2019, the amounts and distribution of the precipitation were adequate to prevent water stress in plants. Nineteen years (50.00%) had water deficiency for 0.5 to 2.0 months during the growing season. Thirteen years (34.21%) had water deficiency conditions for 2.5 to 4.0 months during the growing season. One year (2.63%), 1988, had water deficiency conditions for 5.0 months during the growing season. None of the 38 years had water deficiency conditions for all 6.0 months of the growing season (table 8). The 6-year period (1987-1992) was a long period with low precipitation; during this period, water deficiency conditions existed for an average of 3.1 months during each growing season, which amounts to 51.33% of this period's growing-season months (table 8).

May, June, and July are the 3 most important precipitation months and therefore constitute the primary period of production for range plant communities. May and June are the 2 most important months for dependable precipitation. Only 4 (10.53%) of the 38 years had water deficiency conditions during May, and 4 years (10.53%) had water deficiency conditions during June. One year (2017) had water deficiency conditions in both May and June. Thirteen (34.21%) of the 38 years had water deficiency conditions in July (table 9). Only one year (2017) has had water deficiency conditions during May, June, and July (table 8b).

Most of the growth in range plants occurs in May, June, and July (Goetz 1963, Manske 1994b). Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time when plants have attained 100% of their growth in height (Manske 1994b). Range grass growth coincides with the 3-month period of May, June, and July, when 47.13% of the annual precipitation occurs.

August, September, and October are not dependable for positive water relations. August and September had water deficiency conditions in 47.37% and 50.00% of the years, respectively, and October had water deficiency conditions in 34.21% of the years (table 9). Visual observations of range grasses with wilted, senescent leaves in August indicate that most plants experience some level of water stress when conditions approach those of water deficiency. August, September, and/or October had water deficiency conditions during 81.58% of the growing seasons in the previous 38 years (table 8). These 3 months make up 42% of the growing season, and they had water deficiency conditions on the average of 45% of the time (table 9). The water relations in August, September, and October limit range plant growth and herbage biomass accumulation.

Over the last 38 years, drought years occurred 13.2% of the time. Drought growing seasons occurred 13.2% of the time. Water deficiency months occurred 29.3% of the time. Water deficiency occurred in May and June 10.5% and 10.5% of the time, respectively. July had water deficiency conditions 34.2% of the time. August, September, and October had water deficiency conditions more than 45% of the time. Water deficiency periods lasting for a month place plants under water stress severe enough to reduce herbage biomass production. These levels of water stress are a major factor limiting the quantity and quality of plant growth in western North Dakota and can limit livestock production if not considered during the development and implementation of long-term grazing management strategies.

The ombrothermic procedure to identify growing season months with water deficiency treats each month as an independent event. Precipitation during the other months of the year may buffer or enhance the degree of water stress experienced by perennial plants during water deficiency months. The impact of precipitation during other months on the months with water deficiency can be evaluated from annual running total precipitation data (table 10). Water deficiency conditions did not occur during any months in 2019 (table 10).

Conclusion

The vegetation in a region is a result of the total effect of the long-term climatic factors for that region. Ecologically, the most important climatic factors that affect rangeland plant growth are light, temperature, water (precipitation), and water deficiency.

Light is the most important ecological factor because it is necessary for photosynthesis. Changes in time of year and time of day coincide with changes in the angle of incidence of the sun's rays; these changes cause variations in light intensity. Daylight duration oscillation for each region is the same every year and changes with the seasons. Shading of sunlight by cloud cover and from other plants affects plant growth. Day-length period is important to plant growth because it functions as a trigger to physiological processes. Most cool-season plants reach flower phenophase between mid May and mid June. Most warm-season plants flower between mid June and mid September.

Plant growth is limited by both low and high temperatures and occurs within only a narrow range of temperatures, between 32° and 122° F. Perennial plants have a 6-month growing season, between mid April and mid October. Diurnal temperature fluctuations of warm days and cool nights are beneficial for plant growth. Cool-season plants have lower optimum temperatures for photosynthesis than do warm-season plants, and cool-season plants do not use water as efficiently as do warm-season plants. Temperature affects evaporation rates, which has a dynamic effect on the annual ratios of cool-season to warm-season plants in the plant communities. A mixture of cool- and warm-season plants is highly desirable because the grass species in a mixture of cool- and warm-season species have a wide range of different optimum temperatures and the herbage biomass production is more stable over wide variations in seasonal temperatures.

Water is essential for living systems. Average annual precipitation received at the DREC Ranch is 17.2 inches, with 84.5% occurring during the growing season and 47.1% occurring in May, June, and July. Plant water stress occurs when the rate of water loss through transpiration exceeds the rate of replacement by absorption. Years with drought conditions have occurred 13.2% of the time during the past 38 years. Growing seasons with drought conditions have occurred 13.2% of the time.

Water deficiencies exist when the amount of rainfall received is less than evapotranspiration demand. Temperature and precipitation data can be used in ombrothermic graphs to identify monthly periods with water deficiencies. During the past 38 years, 29.3% of the growing-season months had water deficiency conditions that placed range plants under water stress: range plants were limited in growth and herbage biomass accumulation for an average of 2.0 months during every 6-month growing season. May, June, and July had water deficiency conditions 10.5%, 10.5%, and 34.2% of the time, respectively. August, September, and October had water deficiency conditions 47.4%, 50.0% and 34.2% of the time, respectively. One month with water deficiency conditions causes plants to experience water stress severe enough to reduce herbage biomass production.

Most of the growth in range grasses occurs in May, June, and July. In western North Dakota, 100% of range grass leaf growth in height and 86% to 100% of range flower stalk growth in height are completed by 30 July. Peak aboveground herbage biomass production usually occurs during the last 10 days of July, a period that coincides with the time during which plants are attaining 100% of their height. Most range grass growth occurs during the 3-month period of May, June, and July, when 47.1% of the annual precipitation occurs.

Grassland management should be based on phenological growth stages of the major grasses and can be planned by calendar date. Management strategies for a region should consider the climatic factors that affect and limit range plant growth.

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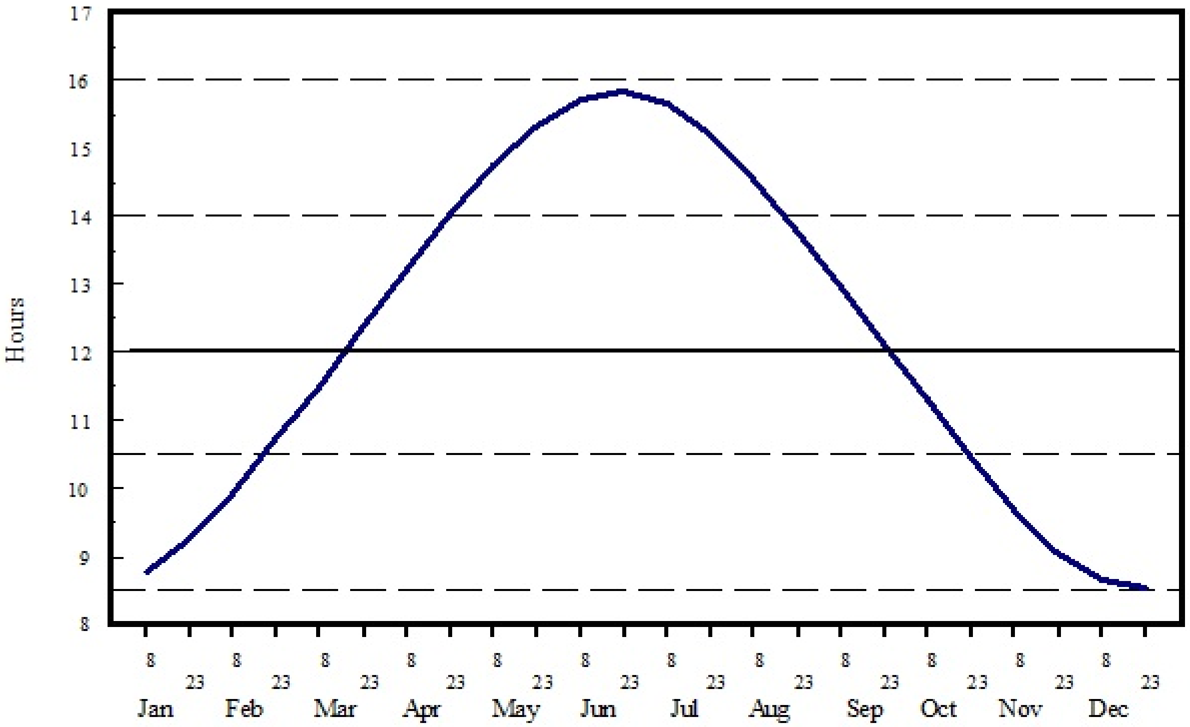

Figure. 1. Annual pattern of daylight duration at Dickinson, North Dakota.

Table 1. Long-term mean monthly temperature and monthly precipitation, 1982-2019.

	° F	**° C**	**in.**	**mm**
Jan	14.72	-9.60	0.43	10.93
Feb	18.28	-7.62	0.44	11.28
Mar	29.21	-1.55	0.76	19.42
Apr	41.58	5.32	1.43	36.28
May	53.63	12.02	2.61	66.31
Jun	63.14	17.30	3.20	81.38
Jul	69.61	20.89	2.33	59.18
Aug	68.37	20.20	1.99	50.62
Sep	56.12	13.87	1.71	43.32
Oct	43.76	6.53	1.33	33.70
Nov	29.08	-1.62	0.56	14.14
Dec	17.72	-7.93	0.47	12.04
	MEAN		**TOTAL**	
	42.10	**5.65**	**17.27**	**438.61**

Table 2. Seasonal precipitation distribution, 1982-2019.

Season	**in.**	**%**
Winter (Jan, Feb, Mar)	1.64	9.49
Spring (Apr, May, Jun)	7.24	41.94
Summer (Jul, Aug, Sep)	6.03	34.91
Fall (Oct, Nov, Dec)	2.36	13.65
TOTAL	**17.27**	

Table 3. Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2019.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2019	1.43	2.61	3.20	2.33	1.99	1.71	1.33	14.60	17.27
1982	1.37	2.69	4.30	3.54	1.75	1.69	5.75	21.09	25.31
% of LTM	95.80	103.07	134.38	151.93	87.94	98.83	432.33	144.48	146.57
1983	0.21	1.53	3.26	2.56	4.45	0.86	0.72	13.59	15.55
% of LTM	14.69	58.62	101.88	109.87	223.62	50.29	54.14	93.10	90.05
1984	2.87	0.00	5.30	0.11	1.92	0.53	0.96	11.69	12.88
% of LTM	200.70	0.00	165.63	4.72	96.48	30.99	72.18	80.08	74.59
1985	1.24	3.25	1.58	1.07	1.84	1.69	2.13	12.80	15.13
% of LTM	86.71	124.52	49.38	45.92	92.46	98.83	160.15	87.69	87.62
1986	3.13	3.68	2.58	3.04	0.46	5.29	0.18	18.36	22.96
% of LTM	218.88	141.00	80.63	130.47	23.12	309.36	13.53	125.77	132.97
1987	0.10	1.38	1.15	5.39	2.65	0.78	0.08	11.53	14.13
% of LTM	6.99	52.87	35.94	231.33	133.17	45.61	6.02	78.99	81.83
1988	0.00	1.85	1.70	0.88	0.03	0.73	0.11	5.30	9.03
% of LTM	0.00	70.88	53.13	37.77	1.51	42.69	8.27	36.31	52.29
1989	2.92	1.73	1.63	1.30	1.36	0.70	0.96	10.60	13.07
% of LTM	204.20	66.28	50.94	55.79	68.34	40.94	72.18	72.61	75.69
1990	2.03	2.39	3.75	1.13	0.31	0.68	0.85	11.14	11.97
% of LTM	141.96	91.57	117.19	48.50	15.58	39.77	63.91	76.31	69.32
1991	1.97	1.16	3.95	1.43	0.55	2.17	1.31	12.54	13.30
% of LTM	137.76	44.44	123.44	61.37	27.64	126.90	98.50	85.90	77.02
1992	0.81	0.68	1.59	2.70	2.02	0.72	0.16	8.68	11.23
% of LTM	56.64	26.05	49.69	115.88	101.51	42.11	12.03	59.46	65.03
1993	1.41	1.71	4.57	5.10	1.24	0.18	0.05	14.26	17.36
% of LTM	98.60	65.52	142.81	218.88	62.31	10.53	3.76	97.69	100.53
1994	0.86	1.46	4.51	1.07	0.31	1.08	4.58	13.87	16.14
% of LTM	60.14	55.94	140.94	45.92	15.58	63.16	344.36	95.02	93.47

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2019.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2019	1.43	2.61	3.20	2.33	1.99	1.71	1.33	14.60	17.27
1995	1.01	4.32	0.68	4.62	3.16	0.00	0.67	14.46	16.24
% of LTM	70.63	165.52	21.25	198.28	158.79	0.00	50.38	99.06	94.05
1996	0.14	3.07	1.86	2.55	1.72	2.51	0.09	11.94	15.97
% of LTM	9.79	117.62	58.13	109.44	86.43	146.78	6.77	81.79	92.48
1997	2.89	0.95	5.02	5.41	0.76	1.75	0.78	17.56	18.61
% of LTM	202.10	36.40	156.88	232.19	38.19	102.34	58.65	120.29	107.77
1998	0.40	1.51	5.98	2.11	4.60	0.71	4.38	19.69	22.42
% of LTM	27.97	57.85	186.88	90.56	231.16	41.52	329.32	134.88	129.84
1999	1.10	4.93	1.59	1.80	2.70	2.40	0.00	14.52	15.56
% of LTM	76.92	188.89	49.69	77.25	135.68	140.35	0.00	99.47	90.11
2000	1.26	1.90	3.77	2.77	2.74	1.09	1.46	14.99	20.23
% of LTM	88.11	72.80	117.81	118.88	137.69	63.74	109.77	102.69	117.15
2001	2.70	0.53	6.36	4.87	0.00	1.94	0.00	16.40	18.03
% of LTM	188.81	20.31	198.75	209.01	0.00	113.45	0.00	112.35	104.41
2002	1.14	2.18	5.40	4.27	4.24	0.74	0.88	18.85	21.88
% of LTM	79.72	83.52	168.75	183.26	213.07	43.27	66.17	129.13	126.71
2003	1.30	4.34	1.42	2.03	0.82	2.37	0.74	13.02	19.12
% of LTM	90.91	166.28	44.38	87.12	41.21	138.60	55.64	89.19	110.73
2004	0.89	1.31	1.65	2.30	0.93	2.57	3.10	12.75	16.51
% of LTM	62.24	50.19	51.56	98.71	46.73	150.29	233.08	87.34	95.61
2005	0.96	6.01	6.05	0.60	1.52	0.50	1.96	17.60	21.51
% of LTM	67.13	230.27	189.06	25.75	76.38	29.24	147.37	120.57	124.57
2006	2.78	2.82	2.13	0.96	2.87	1.42	2.01	14.99	17.70
% of LTM	194.41	108.05	66.56	41.20	144.22	83.04	151.13	102.69	102.50
2007	1.58	4.64	1.80	1.05	0.78	0.76	0.26	10.87	13.94
% of LTM	110.49	177.78	56.25	45.06	39.20	44.44	19.55	74.46	80.73

Table 3 (cont). Precipitation in inches and percent of long-term mean for perennial plant growing season months, 1982-2019.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-Term Mean 1982-2018	1.43	2.61	3.20	2.33	1.99	1.71	1.33	14.60	17.27
2008	0.61	2.79	4.02	1.06	1.02	1.04	1.68	12.22	14.88
% of LTM	42.66	106.90	125.63	45.49	51.26	60.82	126.32	83.71	86.17
2009	1.49	2.47	3.84	3.24	0.95	1.15	1.95	15.09	17.89
% of LTM	104.20	94.64	120.00	139.06	47.74	67.25	146.62	103.37	103.60
2010	1.43	3.70	3.50	1.94	1.39	4.09	0.13	16.18	19.03
% of LTM	100.00	141.76	109.38	83.26	69.85	239.18	9.77	110.84	110.20
2011	1.66	6.87	2.15	2.33	2.70	1.76	0.44	17.91	21.28
% of LTM	116.08	263.22	67.19	100.00	135.68	102.92	33.08	122.69	123.23
2012	2.38	1.58	4.31	1.98	0.82	0.21	2.35	13.63	15.46
% of LTM	166.43	60.54	134.69	84.98	41.21	12.28	176.69	93.37	89.53
2013	1.05	7.55	2.23	2.13	2.81	2.44	3.35	21.56	23.22
% of LTM	73.43	289.27	69.69	91.42	141.21	142.69	251.88	147.70	134.47
2014	1.41	3.73	3.38	0.37	8.84	1.03	0.59	19.35	21.11
% of LTM	98.60	142.91	105.63	15.88	444.22	60.23	44.36	132.56	122.25
2015	0.60	1.65	4.68	2.87	1.69	1.35	1.96	14.80	17.01
% of LTM	41.96	63.22	146.25	123.18	84.92	78.95	147.37	101.39	98.51
2016	3.44	2.26	1.96	3.61	1.86	2.66	1.80	17.59	19.70
% of LTM	240.56	86.59	61.25	154.94	93.47	180.95	135.34	120.50	114.08
2017	1.30	0.84	1.27	0.72	2.67	2.28	0.08	9.16	10.55
% of LTM	90.91	32.18	39.69	30.90	134.17	133.33	6.02	62.75	61.10
2018	0.48	1.22	4.23	2.01	0.55	1.84	0.66	10.99	14.39
% of LTM	33.57	46.74	132.19	86.27	27.64	107.60	49.62	75.29	83.33
2019	1.35	2.52	2.60	1.61	4.70	9.10	1.26	23.14	25.88
% of LTM	94.41	96.55	81.25	69.10	236.18	532.16	94.74	158.52	149.87

Table 4. Years with annual precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	**%LTM**
1	1988	52.29
2	2017	61.10
3	1992	65.03
4	1990	69.32
5	1984	74.59

Table 5. Years with annual precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	**%LTM**
1	2019	149.87
2	1982	146.57
3	2013	134.47
4	1986	132.97
5	1998	129.84
6	2002	126.71

Table 6. Years with growing-season precipitation amounts of 75% or less of the long-term mean (LTM).

	Year	%LTM
1	1988	36.31
2	1992	59.46
3	2017	62.75
4	1989	72.61
5	2007	74.46

Table 7. Years with growing-season precipitation amounts of 125% or more of the long-term mean (LTM).

	Year	%LTM
1	2019	158.52
2	2013	147.70
3	1982	144.48
4	1998	134.88
5	2014	132.56
6	2002	129.13
7	1986	125.77

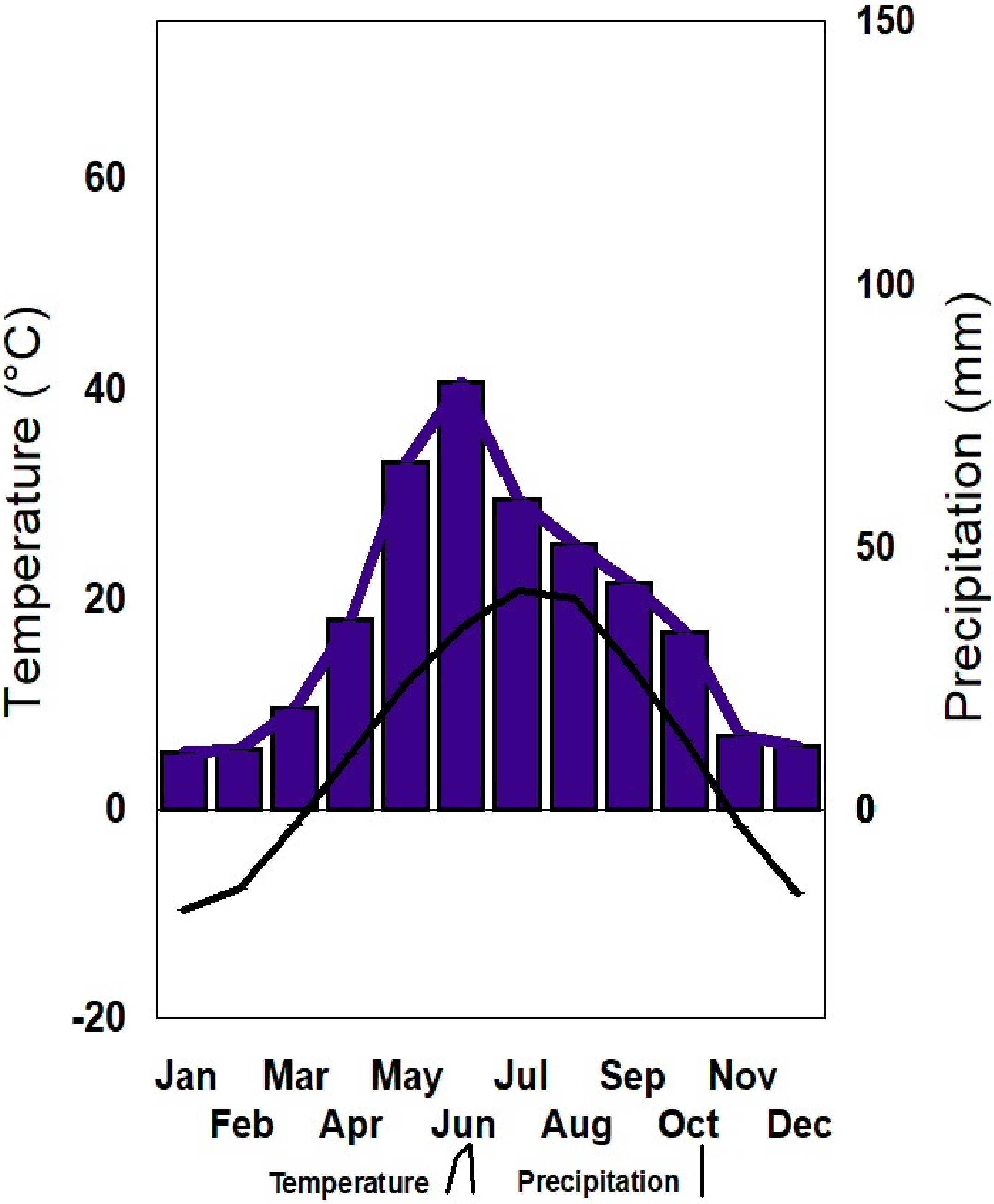

Figure 2. Ombrothermic diagram of long-term mean monthly temperature and monthly precipitation at the DREC Ranch, western North Dakota, 1982-2019.

Table 8a. Growing season months with water deficiency conditions that caused water stress in perennial plants (1982-1989, 1990-1999).

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
1980								-	-
1981	-	-				▨		-	-
1982								0.0	0
1983	▨					▨		1.5	25
1984		▨		▨		▨		3.0	50
1985				▨				1.0	17
1986					▨		▨	1.5	25
1987	▨		▨			▨	▨	3.0	50
1988	▨		▨	▨	▨	▨	▨	5.0	83
1989				▨	▨	▨		3.0	50
								18.0	**38**
1990				▨	▨	▨		3.0	50
1991				▨	▨			2.0	33
1992		▨				▨	▨	2.5	42
1993					▨	▨	▨	2.5	42
1994				▨	▨	▨		3.0	50
1995			▨			▨		2.0	33
1996	▨						▨	1.0	17
1997					▨			1.0	17
1998	▨					▨		1.5	25
1999							▨	0.5	8
								19.0	**32**

Table 8b. Growing season months with water deficiency conditions that caused water stress in perennial plants (2000-2009, 2010-2019).

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
2000						■		1.0	17
2001		■			■		■	2.5	42
2002						■		1.0	17
2003					■			1.0	17
2004					■			1.0	17
2005				■	■	■		3.0	50
2006				■				1.0	17
2007				■	■	■	■	3.5	58
2008				■	■	■		3.0	50
2009					■	■		2.0	33
								19.0	**32**
2010					■		■	1.5	25
2011							■	0.5	8
2012					■	■		2.0	33
2013								0.0	0
2014				■		■	■	2.5	42
2015								0.0	0
2016								0.0	0
2017		■	■	■			■	3.5	58
2018					■			1.0	17
2019								0.0	0
								11.0	**20**

Table 9. Growing season months with water deficiency, 1982-2019.

	APR	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**# Months**	**% 6 Months 15 Apr-15 Oct**
TOTAL	5	4	4	13	18	19	13	67.0	29
% of 38 YEARS	13.2	10.5	10.5	34.2	47.4	50.0	34.2		

Table 10. Monthly precipitation and running total precipitation compared to the long-term mean (LTM), 2019.

	Monthly Precipitation (in)			Running Total Precipitation (in)		
Months	LTM 1982-2018	Precipitation 2019	% of LTM	Running LTM 1982-2018	Running Precipitation 2019	% of LTM
Jan	0.44	0.23	52.27	0.44	0.23	52.27
Feb	0.43	1.12	260.47	0.87	1.35	155.17
Mar	0.77	0.12	15.58	1.65	1.47	89.09
Apr	1.43	1.35	94.41	3.08	2.82	91.56
May	2.61	2.52	96.55	5.69	5.34	93.85
Jun	3.22	2.60	80.75	8.91	7.94	89.11
Jul	2.35	1.61	68.51	11.26	9.55	84.81
Aug	1.92	4.70	244.79	13.18	14.25	108.12
Sep	1.51	9.10	602.65	14.69	23.35	158.95
Oct	1.33	1.26	94.74	16.02	24.61	153.62
Nov	0.55	0.75	136.36	16.57	25.36	153.05
Dec	0.47	0.52	110.64	17.04	25.88	151.88
Total	17.03	25.88	151.88		25.88	151.88

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Plant Water Stress Frequency and Periodicity in Western North Dakota, 1982-2019

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Water stress in plants develops during growing season periods of water deficiency when plants are unable to absorb adequate amounts of water through the roots to match the greater rate of water loss from transpiration. This differential in water loss causes cells to lose turgor resulting in wilting of plant structures. Water stress reduces plant growth and phenological development.

Water deficiency conditions are not the only environmental factors to which perennial grasses respond (Manske 2020). However, variation in frequency and periodicity of growing season months with water deficiencies can account for much of the annual variation in perennial grass herbage biomass production.

Periods of water stress occurrence can be quantitatively determined for growing season months from critical changes in temperature and precipitation data that create water deficiency conditions when precipitation amounts are lower than the variable evapotranspiration rates affected by levels of temperature. Soil water losses increase with increases in evapotranspiration demand. Evaporation rates increase as temperature increases. For each increase of 1 ° C in mean monthly temperature, an increase of 2 mm of monthly precipitation are required to prevent water deficiency and plant water stress.

Plants in water stress have limited growth and herbage biomass accumulation. Water stress can vary in degree from a small decrease in water potential, as in midday wilting on warm, clear days, to the lethal limit of desiccation. Early stages of water stress slow shoot and leaf growth. Leaves show signs of wilting, folding, and discoloration. Tillering and new shoot development decrease. Root production may increase. Senescence of older leaves accelerates. Rates of cell wall formation, cell division, and protein synthesis decrease. As water stress increases, enzyme activity declines and the formation of necessary compounds slows or ceases. The stomata begin to close; this reaction results in decreased rates of transpiration and photosynthesis. Rates of respiration and translocation decrease substantially with increases in water stress. When water stress becomes severe, most functions nearly or completely cease and serious damage occurs. Leaf and root mortality induced by water stress progresses from the tips to the crown. The rate of leaf and root mortality increases with increasing stress. Water stress can increase to a point that is lethal, resulting in damage from which the plant cannot recover. Plant death occurs when meristematic tissue become so dehydrated that cells cannot maintain cell turgidity and biochemical activity (Brown 1995).

A research project was conducted to determine the frequency and periodicity of water stress in perennial rangeland plants of western North Dakota for the 38 year period from 1982 to 2019 using data collected at the DREC ranch located near Manning, North Dakota. A similar complementary report by Manske et al. 2010 covered the 118 year period from 1892 to 2009 using data collected at Dickinson, North Dakota.

Plant water stress develops in plant tissue during growing season months with water deficiency conditions. The frequency, or rate of occurrence, of water stress conditions affects the percentage of total potential quantity and quality of herbage biomass produced by rangeland perennial plants, and the periodicity, or rate of reoccurrence, of water stress conditions affects the percentage of time that rangeland plant production is limited during growing season months.

Procedures

Plant water stress occurs during growing season monthly periods with water deficiency that can be identified by the ombrothermic diagram technique reported by Emberger et al. (1963). This method graphs mean monthly temperature (°C) and monthly precipitation (mm) on the same axis, with the scale of the precipitation data at twice that of the temperature data. The resulting ombrothermic diagram shows monthly periods in which precipitation is greater than the evapotranspiration rate set by the mean monthly temperature and identifies monthly periods with water deficiency conditions, unfavorable periods during which perennial plants experience water stress.

Water deficiency exists during months when the precipitation data bar drops below the temperature data curve. Ombrothermic diagrams were developed from historical climatological data of temperature and precipitation collected during the 38 year period from 1982 through 2019 at the Dickinson Research Extension Center ranch, latitude 47º 14' N, longitude 102º 50' W, Dunn County, near Manning, North Dakota, USA.

The quantity of precipitation received during each growing season was ranked on the basis of % of LTM (long-term mean) and separated into five categories. Growing seasons that received precipitation amounts at less than 50 % of LTM were considered to be in severely dry condition. Growing seasons that received precipitation amounts at less than 75% of LTM were considered to be in dry condition. Growing seasons that received precipitation amounts at greater than 75% and less than 125% of LTM were considered to be in normal condition. Growing seasons that received precipitation amounts at greater than 125% of LTM were considered to be in wet condition. Growing seasons that received precipitation amounts at greater than 150% of LTM were considered to be in extremely wet condition.

Results

The long-term (38 year) mean annual temperature was 42.1º F (5.7º C). January was the coldest month, with a mean temperature of 14.7º F (-9.6º C). July and August were the warmest months, with mean temperatures of 69.6º F (20.9º C) and 68.4º F (20.2º C), respectively (table 1). Perennial grassland plants are capable of active growth for periods longer than the frost-free period. The growing season for perennial plants was considered to be between the first 5 consecutive days in spring and the last 5 consecutive days in fall with the mean daily temperature at or above 32º F (0.0º C). In western North Dakota, the growing season for perennial plants was considered to be generally from mid April through mid October (6.0 months). The long-term mean annual precipitation was 17.3 inches (438.6 mm) (table 1). The growing season precipitation (April to October) was 14.6 inches (370.8 mm), 84.6% of the annual precipitation. The early portion of the growing season (April to July) received 9.6 inches (243.1 mm), 55.5% of the annual precipitation and 65.5% of the growing season precipitation. The latter portion of the growing season (August to October) received 5.0 inches (127.8 mm), 29.1% of the annual precipitation and 34.5% of the growing season precipitation. Total precipitation received during the nongrowing season (November through March) was only 2.7 inches (67.6 mm), 15.4% of the annual precipitation (table 2).

The long-term (38 year) ombrothermic diagram (figure 1) showed near water deficiency conditions during August, September, and October, a finding indicating that rangeland plants generally had difficulty growing and accumulating biomass during these 3 months. Favorable water relations occurred during April, May, June, and July, a period during which rangeland plants were capable of growing and accumulating herbage biomass.

Range plant growth conditions using temperature and precipitation data was determined for growing season months during 1982 to 2019 by the ombrothermic diagram technique and reported in Manske 2020. The summation of the ombrothermic water deficiency data was used to develop table 3. The perennial plant growing season is considered to be 6.0 months long from mid April through mid October. Perennial plants can grow at much lower temperatures than annual plants. The ombrothermic water deficiency conditions are determined for complete months. Water deficiency conditions for April and October are counted as half month periods (table 3).

The 8 year period of 1982 to 1989 has 48 growing season months with water deficiency conditions during 18 months, or 37.5% frequency of the total period months, for a mean of 2.3 months with water deficiency per 6.0 month growing season (table 3). The 10 year period of 1990 to 1999 has 60 growing season months with water deficiency conditions during 19 months, or 31.7% frequency of total period months, for a mean of 1.9 months with water deficiency per 6.0 months growing season (table 3). The 10 year period of 2000 to 2009 has 60 growing season months with water deficiency conditions during 19 months, or 31.7% frequency of total period months, for a mean of 1.9 months with water deficiency per 6.0 months growing season (table 3). The results from the ombrothermic water deficiency data for the 28 year period of 1982 to 2009 conforms extremely well with the long-term ombrothermic water deficiency data for the 118 year period of 1982 to 2009 (Manske et al. 2010) (table 4).

However, the results from the ombrothermic water deficiency data for the 10 year period of 2010 to 2019 does not conform with the long-term ombrothermic water deficiency data for the 118 year period of 1892 to 2009 nor for the 28 year period of 1982 to 2009. The 10 year period of 2010 to 2019 has 60 growing season months with water deficiency conditions during only 11 months, or 18.3% frequency of the total period months, for a mean of 1.1 months with water deficiency conditions per 6.0 month growing season (table 3). In addition, this 10 year period has 4 growing seasons with no water deficient months. No other 10 year period from the long-term regional data has less than 16 months of water deficiency and none have more than 2 growing seasons with no water deficient months. The 10 year period of 2010 to 2019 is an aberration that will be discussed later.

The similarity of the frequency rates of water deficiency months per 6.0 month growing season between the long-term data of 1892 to 2009 with 118 growing seasons and the data of 1982 to 2009 with 28 growing seasons is remarkable. The 118 year period of 1892 to 2009 had 20 wet growing seasons, 16.9%, that received precipitation at greater than 125% of LTM, and the 120 growing season months had water deficiency conditions during 19.5 months, or 16.3% frequency of the total period months, for a mean of 1.0 month with water deficiency per 6.0 month growing season (table 4). The 28 year period of 1982 to 2009 had 4 wet growing seasons, 14.3%, that received precipitation at greater than 125% of LTM, and the 24 growing season months had water deficiency conditions during 4.0 months, or 16.7% frequency of the total period months, for a mean of 1.0 month with water deficiency per 6.0 month growing season (table 4).

The 118 year period had 4 severely dry growing seasons, 3.4%, that received precipitation at less than 50% of LTM, and the 24 growing season months had water deficiency conditions during 18.0 months, or 75.0% frequency of the total period months, for a mean of 4.5 months with water deficiency per 6.0 month growing season (table 4). The 28 year period had 1 severely dry growing season, 3.6%, that received precipitation at less than 50% of LTM, and the 6 growing season months had water deficiency conditions during 5.0 months, or 83.3% frequency of the total period months, for a mean of 5.0 months with water deficiency per 6.0 month growing season (table 4).

The 118 year period had 14 dry growing seasons, 11.9%, that received precipitation at less than 75% of LTM, and the 84 growing season months had water deficiency conditions during 44.0 months, or 52.4% frequency of the total period months, for a mean of 3.1 months with water deficiency per 6.0 month growing season (table 4). The 28 year period had 3 dry growing seasons, 10.7%, that received precipitation at less than 75% of LTM, and the 18 growing season months had water deficiency conditions during 9.0 months, or 50.0% frequency of the total period months, for a mean of 3.0 months with water deficiency per 6.0 month growing season (table 4).

The 118 year period had 80 normal growing seasons, 67.8%, that received precipitation at greater than 75% and less than 125% of LTM, and the 480 growing season months had water deficiency conditions during 150.0 months, or 31.3% frequency of the total period months, for a mean of 1.9 months with water deficiency per 6.0 month growing season (table 4). The 28 year period had 20 normal growing seasons, 71.4%, that received precipitation at greater than 75% and less than 125% of LTM, and the 120 growing season months had water deficiency conditions during 38.0 months, or 31.7% frequency of the total period months, for a mean of 1.9 months with water deficiency per 6.0 month growing season (table 4).

The total 118 growing seasons from the years of 1892 to 2009, received precipitation at the wet, dry, and normal % of LTM, and the 708 growing season months had water deficiency conditions during 231.5 months, or 32.7% frequency of the total period months, for a mean of 2.0 months with water deficiency per 6.0 month growing season (table 4). The total 28 growing seasons from the years of 1982 to 2009, received precipitation at the wet, dry, and normal % of LTM, and the 168 growing season months had water deficiency conditions during 56.0 months, or 33.3% frequency of the total period months, for a mean of 2.0 months with water deficiency per 6.0 month growing season (table 4). The typical 6.0 month growing season from the period of 1892 to 2009 had 2.0 months with water deficiency conditions. The typical 6.0 month growing season from the period of 1982 to 2009 had 2.0 months with water deficiency conditions. The typical 6.0 month growing season for the past 118 years has had a mean of 2.0 months with water deficiency. That has been the normal growing season in western North Dakota.

Most Northern Plains agricultural producers manage the land with the assumption that the typical 6.0 month growing season should receive adequate levels of precipitation that result in zero months with water deficiency conditions. Unfortunately, growing seasons that have zero months with water deficiency are rare in western North Dakota. During the 118 growing seasons of 1893 to 2009, growing seasons that had zero months with water deficiency only occurred seven times, 1912, 1920, 1941, 1951, 1982, 1985, and 1998, for a long-term frequency of occurrence of 5.9% of the growing seasons, at about 1 growing season without water deficiency in 16 or 17 years (Manske et al. 2010). During the 28 growing seasons of 1982 to 2009, growing seasons that had zero months with water deficiency only occurred one time, 1982, for a long-term frequency of occurrence of 3.6% of the growing seasons, at 1 growing season without water deficiency in 28 years (table 3).

During the 10 growing seasons of 2010 to 2019, growing seasons that had zero months with water deficiency occurred four times, 2013, 2015, 2016, and 2019, for a remarkable frequency of 40% of the growing seasons, at a mean of 1 growing season without water deficiency in 2.5 years (table 3). The 2019 growing season had extremely wet conditions from receiving 23.14 inches of precipitation at 158.52% of LTM, and had a mean of 3.31 inches of rain per month. The 2013 growing season had wet conditions from receiving 21.56 inches of precipitation at 147.70% of LTM, and had a mean of 3.08 inches of rain per month. The 2015 and 2016 growing seasons had normal conditions from receiving a mean of 16.20 inches of precipitation at 110.95% of LTM, and had a mean of 2.31 inches of rain per month. The 10 year mean growing season precipitation received was 16.43 inches, 112.53% of LTM, and had a mean of 2.35 inches of rain per month. This decade of aberrations had 60 growing season months with water deficiency condition during only 11 months, or 18.3% frequency of the total period months, for a mean of 1.1 month with water deficiency per 6.0 month growing season.

No other ten year period than 2010 to 2019 has had as few as 11 months with water deficiency, for only 18.3% frequency of the total decade growing season months. The ten year period of 1920 to 1929 had the second fewest at 16 months with water deficiency, for 26.7% frequency of the total decade growing season months. The ten year period of 1930 to 1939 had the greatest amount of water deficient months in recorded weather data for western North Dakota at 25 months, for 41.7% frequency of the total decade growing season months.

No other ten year period than 2010 to 2019 has had as great of a mean growing season precipitation amount as 16.43 inches (112.53% of LTM) per 6.0 month growing season. The ten year period of 1940 to 1949 had the second greatest mean growing season precipitation with an 8.1% reduction at 15.10 inches (103.42% of LTM) per 6.0 month growing season. The ten year period of 1970 to 1979 had the third greatest mean growing season precipitation with an 8.5% reduction at 15.04 inches (103.01% of LTM) per 6.0 month growing season.

The eight year period of 1982 to 1989 had a mean growing season precipitation amount with a 20.2% reduction at 13.12 inches (89.86% of LTM) per 6.0 month growing season. The ten year period of 1990 to 1999 had a mean growing season precipitation amount with a 15.6% reduction at 13.87 inches (95.00% of LTM) per 6.0 month growing season. The ten year period of 2000 to 2009 had a mean growing season precipitation amount with a 10.7% reduction at 14.68 inches (100.55% of LTM) per 6.0 month growing season.

The 10 year period of 2010 to 2019 is distinctly dissimilar to any other 10 year period in 128 years in western North Dakota and had 1 growing season with extremely wet conditions from a mean of 23.14 inches of precipitation at 158.52% of LTM, and had a mean of 0.0 months with water deficiency per 6.0 month growing season. This 10 year period had 2 growing seasons with wet conditions from a mean of 20.46 inches of precipitation at 140.13% of LTM, and had a mean of 1.3 months with water deficiency per 6.0 month growing season. This 10 year period had 6 growing seasons with normal conditions from a mean of 15.18 inches of precipitation at 104.01% of LTM, and had a mean of 0.8 months with water deficiency per 6.0 month growing season. This 10 year period had 1 growing season with dry conditions from a mean of 9.16 inches of precipitation at 62.75% of LTM, and had a mean of 3.5 months with water deficiency per 6.0 month growing season (table 5).

The combined 28 year period of 1982 to 2009 had 4 growing seasons with wet conditions from a mean of 19.50 inches of precipitation at 133.56% of LTM, and had a mean of 1.0 months with water deficiency per 6.0 month growing season. This 28 year period had 20 growing seasons with normal conditions from a mean of 13.85 inches of precipitation at 94.86% of LTM, and had a mean of 1.9 months of water deficiency per 6.0 month growing season. This 28 year period had 3 growing seasons with dry conditions from a mean of 10.05 inches of precipitation at 68.84% of LTM, and had a mean of 3.0 months of water deficiency per 6.0 month growing season. This 28 year period had 1 growing season with severely dry conditions from a mean of 5.30 inches of precipitation at 36.31% of LTM, and had a mean of 5.0 months of water deficiency per 6.0 month growing season.

The 8 year period 1982 to 1989 had 2 growing seasons with wet conditions from a mean of 19.73 inches of precipitation at 135.13% of LTM, and had a mean of 0.8 months with water deficiency per 6.0 month growing season. This 8 year period had 4 growing seasons with normal conditions from a mean of 12.40 inches of precipitation at 84.97% of LTM, and had a mean of 2.1 months with water deficiency per 6.0 month growing season. This 8 year period had 1 growing season with dry conditions from a mean of 10.60 inches of precipitation at 72.61% of LTM, and had a mean of 3.0 months with water deficiency per 6.0 month growing season. This 8 year period had 1 growing season with severely dry conditions from a mean of 5.30 inches of precipitation at 36.31% of LTM, and had a mean of 5.0 months with water deficiency per 6.0 month growing season (table 5).

The ten year period of 1990 to 1999 had 1 growing season with wet conditions from a mean of 19.69 inches of precipitation at 134.88% of LTM, and had a mean of 1.5 months with water deficiency per 6.0 month growing season. This 10 year period had 8 growing seasons with normal conditions from a mean of 13.79 inches of precipitation at 94.44% of LTM, and had a mean of 1.9 months with water deficiency per 6.0 month growing season. This 10 year period had 1 growing season with dry conditions from a mean of 8.68 inches of precipitation at 59.46% of LTM, and had a mean of 2.5 months with water deficiency per 6.0 month growing season (table 5).

The ten year period of 2000 to 2009 had 1 growing season with wet conditions from a mean of 18.85 inches of precipitation at 129.13% of LTM, and had a mean of 1.0 month with water deficiency per 6.0 month growing season. This 10 year period had 8 growing seasons with normal conditions from a mean of 14.63 inches of precipitation at 100.24% of LTM, and had a mean of 1.8 months with water deficiency per 6.0 month growing season. This 10 year period had 1 growing season with dry conditions from a mean of 10.87 inches of precipitation at 74.46% of LTM, and had a mean of 3.5 months with water deficiency per 6.0 month growing season (table 5).

We do not know the complete reason why the weather conditions during the decade of 2010 to 2019 were so different from any other decade in the 128 years of recorded weather data for western North Dakota. The global climate has been experiencing various levels of change for some time. Polar and glacial ice has been melting at higher rates than in the past because of an increase in average world temperature and has caused a measurable rise in sea level. There has been an increase in the quantity of carbon dioxide (CO_2), nitrogenoxides (NO), ozone (O_3), methane (CH_4), and chlorofluorcarbons (chlorine (CI) and/or fluorine (F) added to hydrocarbons) occurring in the atmosphere. Water vapor makes up about 95% of the worlds greenhouse gases which absorb infrared radiation and reflect it back to earth which is an absolutely essential natural phenomenon required for life to exist on earth but this process might be working a little harder than needed.

A ten year period is too short of a time period to show what the future climate change for the Northern Plains will eventually be. However, the factors that change the global climate must have had some effect on the increase in the quantity and distribution of precipitation during this ten year period. We would need these conditions to continue for another ten to twenty years before it could be labeled as climate change.

Other than factors that change global climates, there are two factors that may have also contributed to this ten year increase in regional precipitation levels. These are: from the changes in increased atmospheric water vapor resulting from increased water evaporation off the surfaces of Lake Sakakawea, Lake Oahe, and Fort Peck Lake, and from the precautionary practice of cloud seeding with silver iodide (AgI) and dry ice (solid CO_2) to reduce the degree and extent of damage from hail. Unfortunately, these factors have not been quantified and the degree of their influence, if any, is not known.

Periodicity as percent of reoccurrence of water deficiency conditions during growing season months was not evenly distributed. Percent periodicity of water deficiency follow similar patterns during the periods of 1892 to 2009 and 1982 to 2009 (table 6). April had water deficiency around 17% to 18% of the time. May and June had water deficiency around 10% to 14% of the time. July had water deficiency around 38% to 39% of the time. August had water deficiency around 53% to 54% of the time. September had a wider range of water deficiency during 50% to 60% of the time. October had water deficiency around 32% to 47% of the time (table 6). April, May, and June had relatively low periodicity of water deficiency. July and October had relatively moderate periodicity of water deficiency. August and September had relatively high periodicity of water deficiency for greater than half the time (table 6).

Percent periodicity of water deficiency during 2010 to 2019 followed a pattern quite dissimilar to that of 1892 to 2009 and 1982 to 2009 (table 6). April had no water deficiency conditions. May, June, July, and September had relatively low periodicity of reoccurrence of water deficiency at around 10% to 20%. August had low moderate periodicity of water deficiency at 30% of the time. October had moderate periodicity of water deficiency at 40% of the time (table 6). The period of 2010 to 2019 only had a total of 11 growing season months with water deficiency at a low frequency rate of 18.3% which had never been this low of growing season months with water deficiency during the past 128 years in western North Dakota.

The early portion of the growing season, April to July, received a mean of 65.5% of the growing season precipitation. The latter portion of the growing season, August to October, received a mean of 34.5% of the growing season precipitation. Rangeland perennial plants produced most of their growth in leaf and flower stalk height (Goetz 1963) and in herbage biomass weight (Manske 1994) during the early portion of the growing season, May, June, and July, because of the low periodicity of water deficiency and the generally advantageous water conditions. The high periodicity of water deficiency conditions during August, September, and October limited rangeland plant growth and herbage biomass accumulation.

Discussion

The 6.0 month perennial plant growing season, mid April to mid October, had water deficiency conditions at a frequency of 33.3% during the 28 year period of 1982 to 2009, and at a frequency of 32.7% during the 118 year period of 1892 to 2009, for a mean of 2.0 months with water deficiency per 6.0 month growing season. The frequency of one third of the growing season months with water deficiency was the normal weather conditions for western North Dakota for 118 years. The recent decade of 2010 to 2019, which has had some effect from the factors that change global climate, had increased quantities of precipitation, improved distribution of precipitation, and reduced frequency of water deficiency to 18.3%, for a mean of only 1.1 months with water deficiency per 6.0 months growing season.

Growing seasons that have zero months with water deficiency are the ideal conditions that agricultural producers plan for or at least hope for. But in western North Dakota, growing seasons that had no water deficiency were abnormal events. During the 118 year period of 1892 to 2009, growing seasons with no water deficiency occurred at the low frequency of 5.9% of the years. During the 28 year period of 1982 to 2009, growing seasons with no water deficiency occurred at a lower frequency of 3.6% of the years. This low frequency of occurrence changed during the recent decade of 2010 to 2019 to a rate of 40.0% of the years, which may or may not continue into future decades.

The quantity of precipitation received during a growing season was variable and affected perennial plant growth differently. During the 28 year period of 1982 to 2009, precipitation received in amounts less than 50% of LTM caused severely dry conditions during 3.6% of the growing seasons, precipitation received in amounts less than 75% of LTM caused dry conditions during 10.7% of the growing seasons, precipitation received in amounts greater than 75% and less than 125% of LTM caused normal conditions during 71.4% of the growing seasons, precipitation received in amounts greater than 125% of LTM caused wet conditions during 14.3% of the growing seasons, and no growing seasons received greater than 150% of LTM. During the 118 year period of 1892 to 2009, precipitation was received at very similar rates, precipitation received in amounts less than 50% of LTM caused severely dry conditions during 3.4% of the growing seasons, precipitation received in amounts less than 75% of LTM caused dry conditions during 11.9% of the growing seasons, precipitation received in amounts greater than 75% and less than 125% of LTM caused normal conditions during 67.8% of the growing seasons, precipitation received in amounts greater than 125% of LTM caused wet conditions during 16.9% of the growing seasons, and no growing seasons received greater than 150% of LTM. During the recent decade of 2010 to 2019 precipitation was received at greater rates and with improved distribution, precipitation was not received in amounts less than 50% of LTM, precipitation received in amounts less than 75% of LTM caused dry conditions during 10.0% of the growing seasons, precipitation received in amounts greater than 75% and less than 125% of LTM caused normal conditions during 60.0% of the growing seasons, precipitation received in amounts greater than 125% of LTM caused wet conditions during 20.0% of the growing seasons, precipitation received in amounts greater than 150% of LTM caused extremely wet conditions during 10.0% of the growing seasons.

The growing seasons of the period of 1982 to 2009, had water deficiency conditions that reoccurred at a mean periodicity rate of 19.7% during the months, April to July, in the early portion of the growing season and reoccurred at a mean periodicity rate of 48.8% during the months, August to October, in the latter portion of the growing season. The growing seasons of the period of 1892 to 2009, had water deficiency conditions that reoccurred at a similar mean periodicity rates of 19.7% during the months, April to July, in the early portion of the growing season and reoccurred at a mean periodicity rate of 49.6% during the months, August to October, in the latter portion of the growing season. The growing seasons of the recent decade of 2010 to 2019, had water deficiency conditions that reoccurred at very dissimilar mean periodicity rates of 10% during the months, April to July, in the early portion of the growing season and reoccurred at a mean periodicity rate of 30.0% during the months, August to October, in the latter portion of the growing season.

Water deficiency conditions during growing season months has remained at the same mean frequency rate of 33%, for a mean of 2.0 months with water deficiency per 6.0 month growing season during the past 28 year period of 1982 to 2009 and the past 118 year period of 1892 to 2009. This long-term frequency rate of growing season months with water deficiency has caused sufficient water stress in perennial rangeland plants that have limited herbage biomass productivity in quantity and quality that has, subsequently, resulted in reduced livestock weight performance.

Frequency rate of growing season months with water deficiency improved with an increase in quantity of precipitation and improvement in water distribution during the recent decade of 2010 to 2019. If these conditions continue into the future, we will need to make upward adjustments to our pasture stocking rates and heavier calf weaning weights. On the other hand, if these conditions do not continue, the future climate change for the Northern Plains won't be as bountiful as the past decade of 2010 to 2019.

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Table 1. Long-term mean temperature and precipitation, 1982-2019.

		Mean Monthly Temperature		Monthly Precipitation	
		°F	°C	in.	mm
🟥	Jan	14.72	-9.60	0.43	10.93
🟥	Feb	18.28	-7.62	0.44	11.28
🟥	Mar	29.21	-1.55	0.76	19.42
🟩	Apr	41.58	5.32	1.43	36.28
🟩	May	53.63	12.02	2.61	66.31
🟩	Jun	63.14	17.30	3.20	81.38
🟩	Jul	69.61	20.89	2.33	59.18
🟨	Aug	68.37	20.20	1.99	50.62
🟨	Sep	56.12	13.87	1.71	43.32
🟨	Oct	43.76	6.53	1.33	33.70
🟥	Nov	29.08	-1.62	0.56	14.14
🟥	Dec	17.72	-7.93	0.47	12.04
		MEAN		**TOTAL**	
		42.10	5.65	17.26	438.61

Table 2. Seasonal precipitation distribution.

		Inches	Percent
	Average Annual Precipitation	17.26	
	Growing Season (Apr-Oct)	14.60	(84.59%)
🟩	Apr, May, Jun, Jul	9.57	(55.45%)
🟨	Aug, Sep, Oct	5.03	(29.14%)
🟥	Nongrowing Season (Nov-Mar)	2.66	(15.41%)

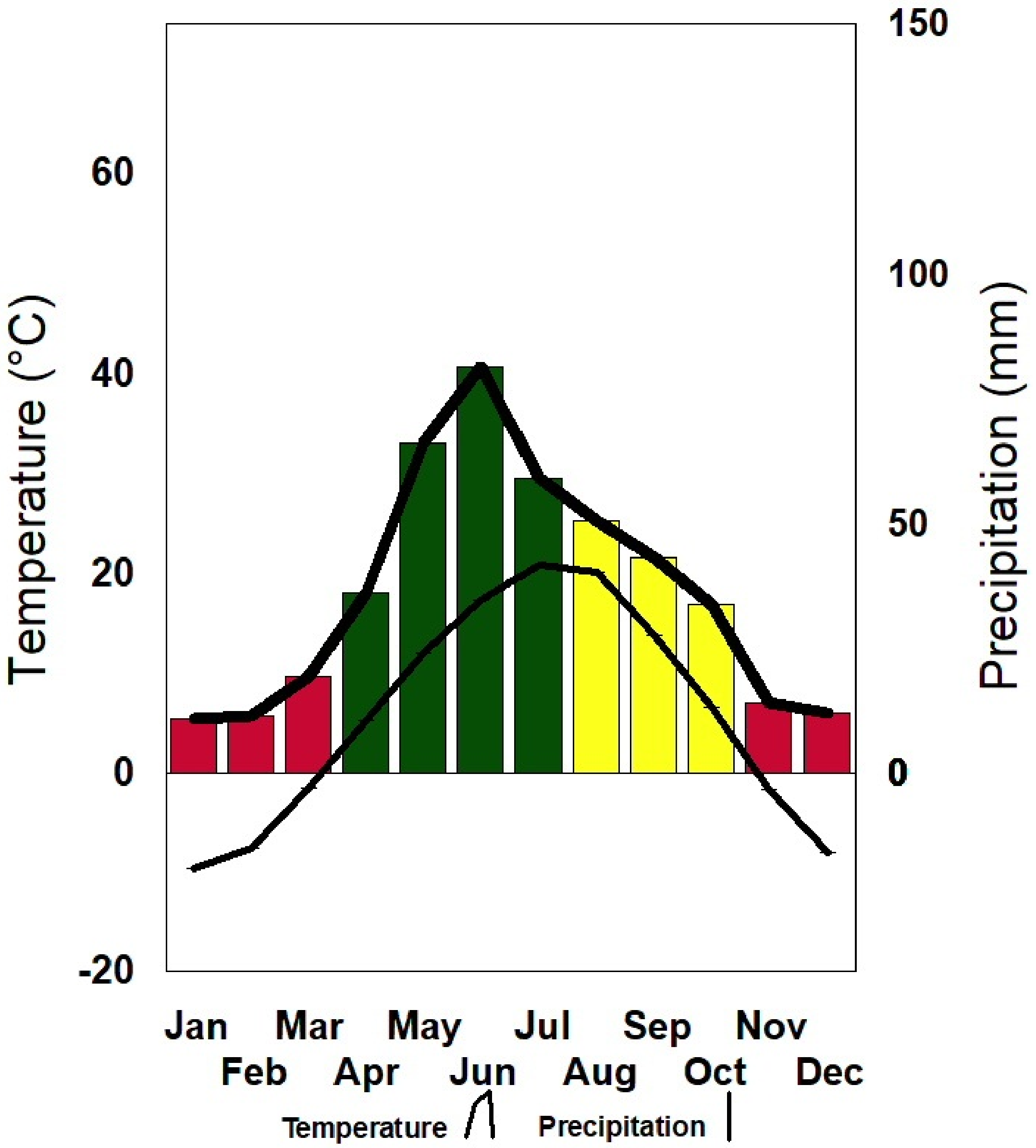

Figure 1. Ombrothermic diagram of long-term mean monthly temperature and monthly precipitation at the DREC Ranch, western North Dakota, 1982-2019.

Table 3. Growing season months with water deficiency conditions that caused water stress in perennial plants.

	Apr	May	Jun	Jul	Aug	Sep	Oct		Apr	May	Jun	Jul	Aug	Sep	Oct
1980	**No Data**							**2000**						🟥	
1981	**No Data**							**2001**		🟥			🟥		🟥
1982	🟨	🟨	🟨	🟨	🟨	🟨	🟨	**2002**						🟥	
1983	🟥					🟥		**2003**					🟥		
1984		🟥		🟥		🟥		**2004**					🟥		
1985				🟥				**2005**				🟥	🟥	🟥	
1986					🟥		🟥	**2006**				🟥			
1987	🟥		🟥			🟥	🟥	**2007**				🟥	🟥	🟥	🟥
1988	🟥		🟥	🟥	🟥	🟥	🟥	**2008**				🟥	🟥	🟥	
1989				🟥	🟥	🟥		**2009**					🟥	🟥	
1990				🟥	🟥	🟥		**2010**					🟥		🟥
1991				🟥	🟥			**2011**							🟥
1992		🟥				🟥	🟥	**2012**					🟥	🟥	
1993					🟥	🟥	🟥	**2013**	🟨	🟨	🟨	🟨	🟨	🟨	🟨
1994				🟥	🟥	🟥		**2014**				🟥		🟥	🟥
1995			🟥			🟥		**2015**	🟨	🟨	🟨	🟨	🟨	🟨	🟨
1996	🟥						🟥	**2016**	🟨	🟨	🟨	🟨	🟨	🟨	🟨
1997					🟥			**2017**		🟥	🟥	🟥			🟥
1998	🟥					🟥		**2018**					🟥		
1999							🟥	**2019**	🟨	🟨	🟨	🟨	🟨	🟨	🟨

1982-2019 38 Years

🟥 Months with water deficiency

🟨 Year with no water deficiency

Table 4. Comparison of growing season (GS) months with water deficiency (WD) conditions at Dickinson, 1892-2009, 118 growing seasons and at DREC ranch, 1982-2009, 28 growing seasons, both in western North Dakota.

118 GS, 1892-2009, Dickinson					28 GS, 1982-2009, DREC ranch				
No. of GS	Period GS months	No. of WD months	% of months WD	No. of months WD/6.0 mo. GS	No. of GS	Period GS months	No. of WD months	% of months WD	No. of months WD/6.0 mo. GS
Wet Growing Seasons with Precipitation greater than 125% of LTM									
20	120	19.5	16.3%	1.0/6.0 mo. GS	4	24	4.0	16.7%	1.0/6.0 mo. GS
Severely Dry Growing Seasons with Precipitation less than 50% of LTM									
4	24	18.0	75.0%	4.5/6.0 mo. GS	1	6	5.0	83.3%	5.0/6.0 mo. GS
Dry Growing Seasons with Precipitation less than 75% of LTM									
14	84	44.0	52.4%	3.1/6.0 mo. GS	3	18	9.0	50.0%	3.0/6.0 mo. GS
Normal Growing Seasons with Precipitation greater than 75% and less than 125% of LTM									
80	480	150.0	31.3%	1.9/6.0 mo. GS	20	120	38.0	31.7%	1.9/6.0 mo. GS
Total Growing Seasons with Precipitation at Wet, Dry, and Normal % of LTM									
118	708	231.5	32.7%	2.0/6.0 mo. GS	28	168	56.0	33.3%	2.0/6.0 mo. GS

Table 5. Plant Water Stress feasibility as affected by quantity of growing season (GS) precipitation received ranked by % LTM and the resulting number of months with water deficiency (WD) during four decade periods.

Growing Season Condition Precipitation Rank		% LTM	1982-1989 8 yrs #GS	 WD mo.	1990-1999 10 years #GS	 WD mo.	2000-2009 10 years #GS	 WD mo.	2010-2019 10 years #GS	 WD mo.
Severely Dry		<50%	1	5.0	0	-	0	-	0	-
Dry		<75%	1	3.0	1	2.5	1	3.5	1	3.5
Normal	>75%	<125%	4	2.1	8	1.9	8	1.8	6	0.8
Wet		>125%	2	0.8	1	1.5	1	1.0	2	1.3
Extremely Wet		>150%	0	-	0	-	0	-	1	0.0

Table 6. Periodicity as percent of reoccurrence of water deficiency (WD) during growing season (GS) months from three study periods.

Growing Seasons Periods	#WD mo. % of yrs	Apr	May	Jun	Jul	Aug	Sep	Oct	Total WD mo.	WD mo. per GS
1892-2009 118 yrs	# WD mo.	20	16	12	45	62	59	55	231.5	2.0
	% of yrs	16.9	13.6	10.2	38.1	52.5	50.0	46.6	32.7%	
1982-2009 28 yrs	# WD mo.	5	3	3	11	15	17	9	56.0	2.0
	% of yrs	17.9	10.7	10.7	39.3	53.6	60.7	32.1	33.3%	
2010-2019 10 yrs	# WD mo.	0	1	1	2	3	2	4	11.0	1.1
	% of yrs	0.0	10.0	10.0	20.0	30.0	20.0	40.0	18.3%	

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