

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. 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 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 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 determined by the recycling rates of soil organic matter decomposition and mineralization that are directly regulated by the biomass of active rhizosphere microorganisms.

The ecosystem source for all of the minor essential elements required by animals and plants is weathered parent material. The elemental content of

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 through 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 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). 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 gradually 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 brome grass, 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 immobile 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 (NH₄). 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 Pflieger 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 brome grass), 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 programmed 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/m³ per year from year 3 to 6, reaching a weight of 214.3 kg/m³, 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/m³ 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/m³, 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 than 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 exuded 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 mobilized 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 Koehy 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 maintenance (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 brome grass 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 exuded from the grass roots into the rhizosphere zone. Without partial defoliation by grazing, only a small quantity of short carbon chain energy leaks from the grass roots into the rhizosphere; this low amount of simple carbon compounds is barely enough to sustain a 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 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 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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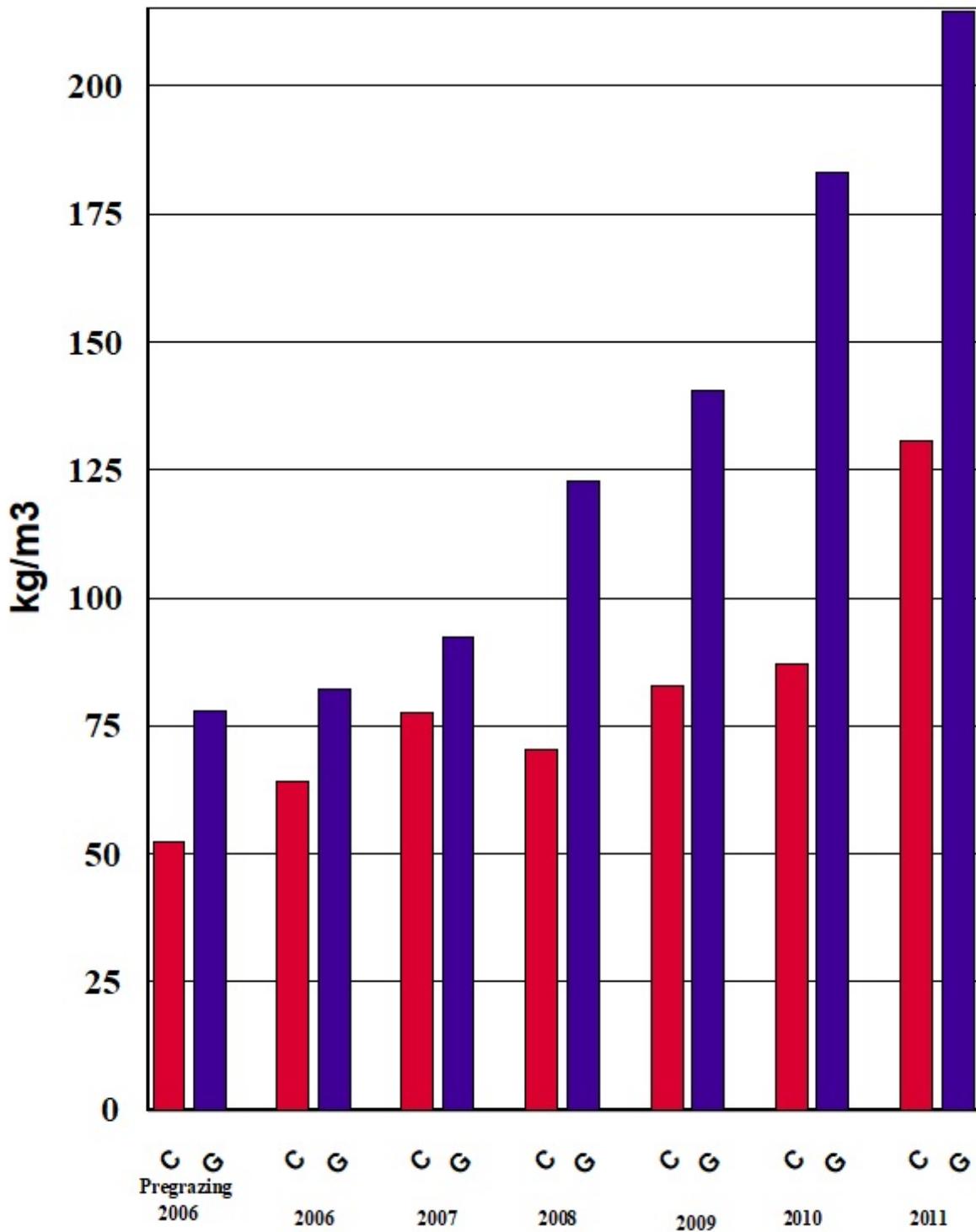


Figure 1. Rhizosphere weight (kg/m³) for the control pasture (red) and grazed pastures (blue) during six years of twice-over rotation management, 2006-2011.

Table 2. Rhizosphere weight (kg/m³) 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 (cm³/m³), 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.

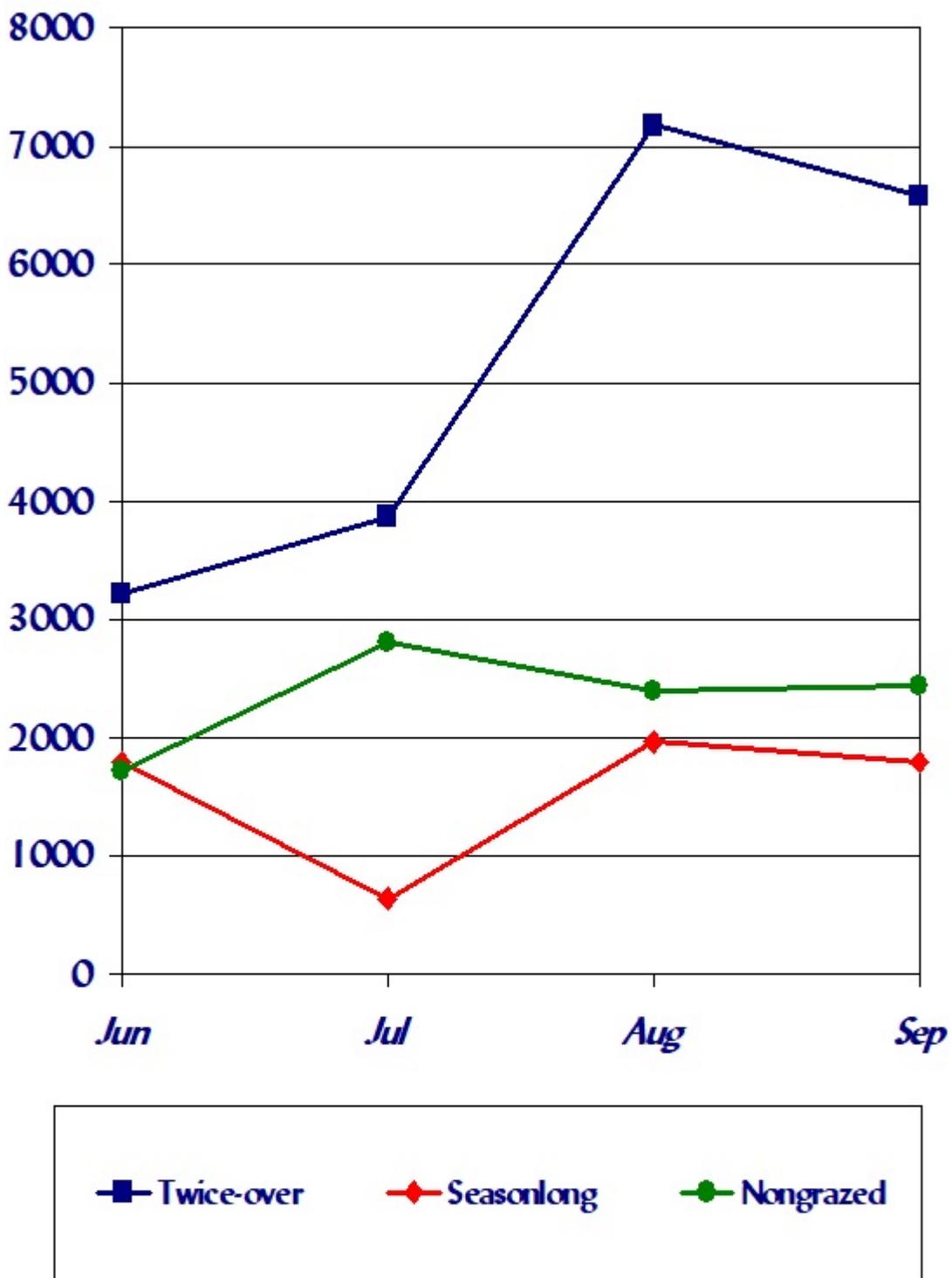


Figure 2. Rhizosphere volume (cm³) per cubic meter of soil

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

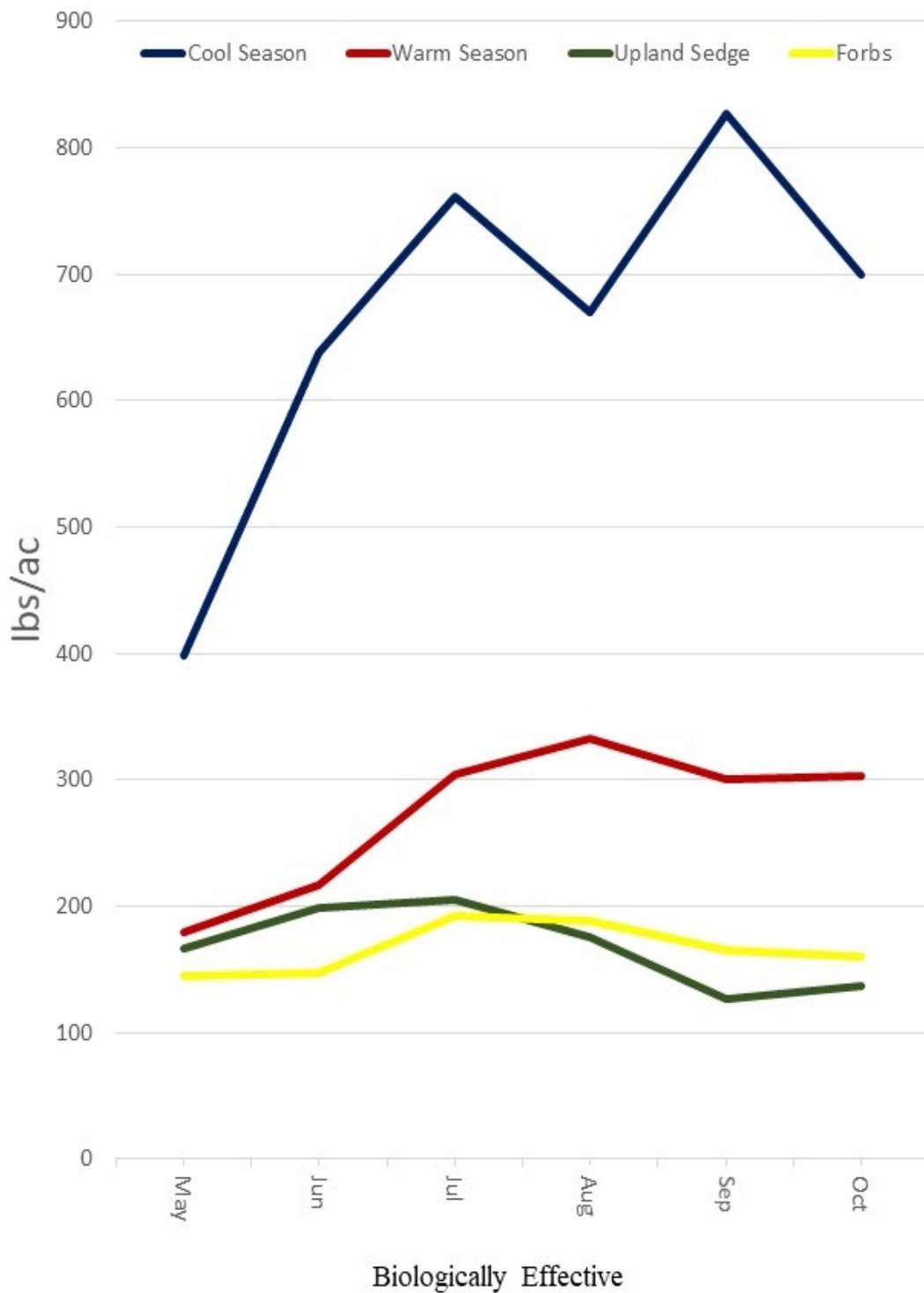


Figure 3. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Biologically Effective concept, 1983-2012.

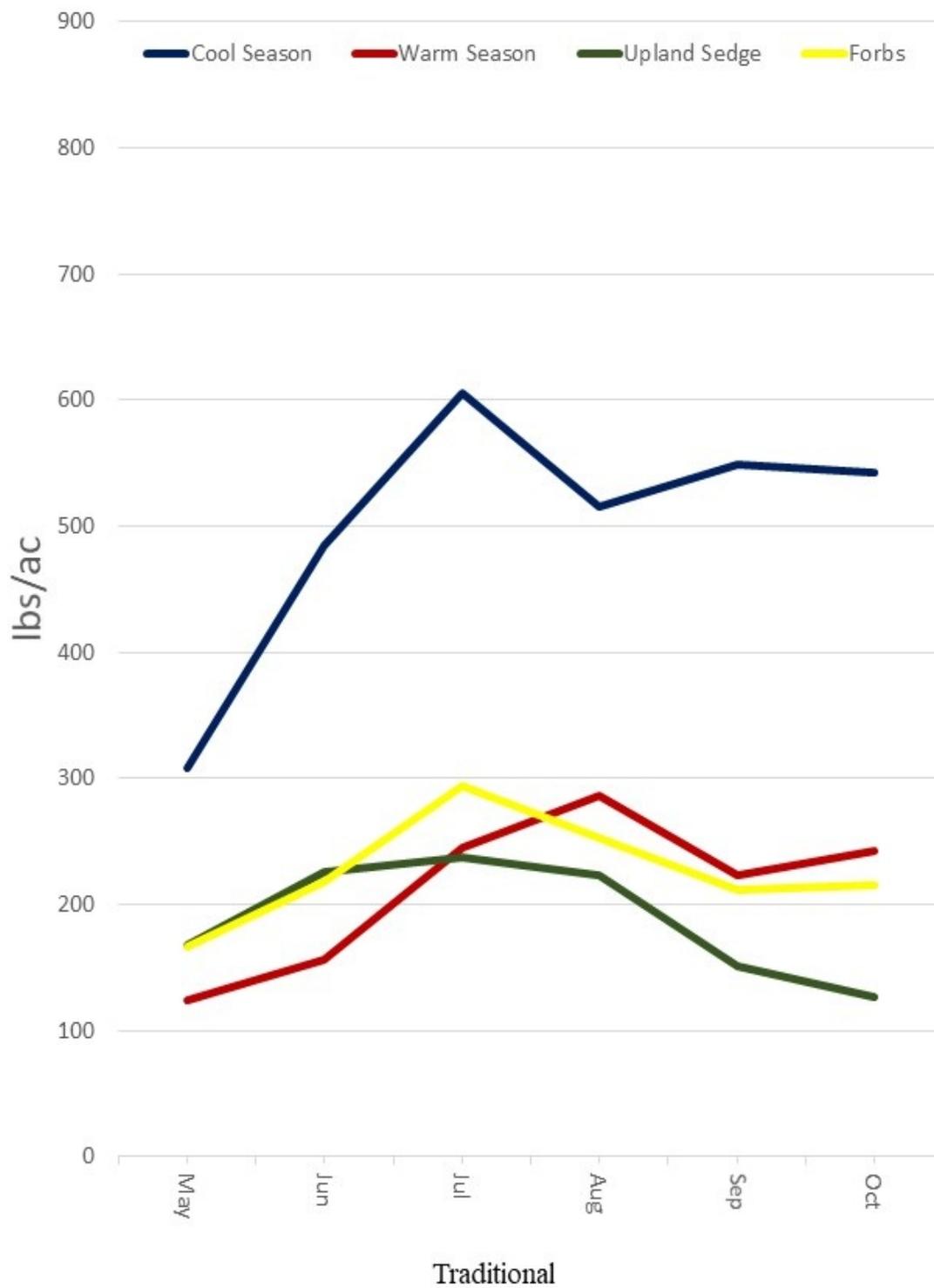


Figure 4. Mean monthly herbage biomass (lbs/ac) by biotypes on the silty site of the Traditional concept, 1983-2012.

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.

Native Rangeland	Traditional Concept			Biologically Effective Concept			Biological Gain		
	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.

Native Rangeland	Traditional Concept				Biologically Effective Concept				Value Captured Gain			
	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

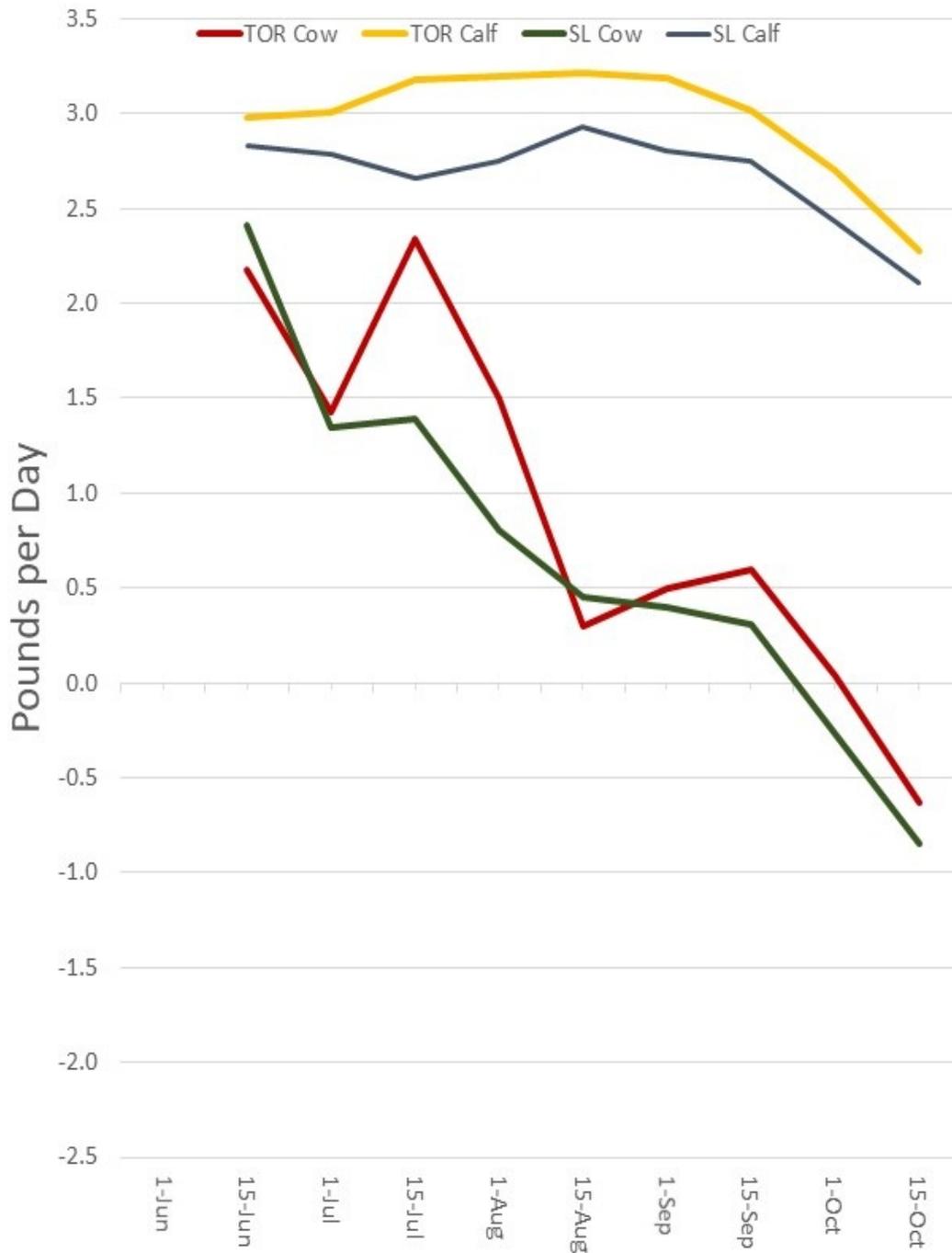


Figure 5. Cow and calf daily gain on the seasonlong and twice-over grazing systems, 1995-2005.

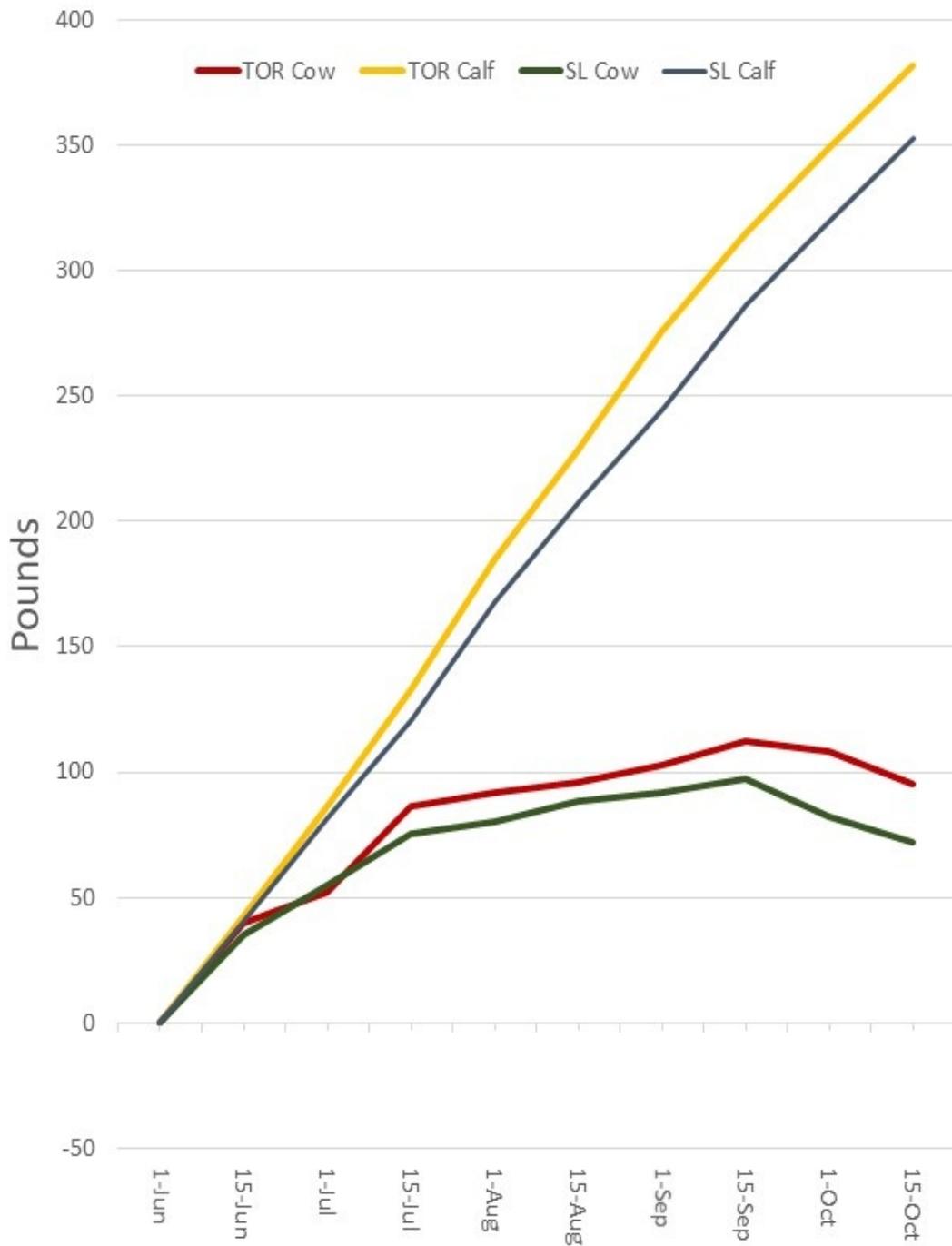


Figure 6. Cow and calf accumulated weight gain on the seasonlong and twice-over grazing systems, 1995-2005.

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