Soil Mineral Nitrogen Increased Above the Threshold Quantity of 100 Pounds per Acre in Rangeland Ecosystems

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Rangelands are valuable assets to livestock agriculture in the Northern Plains and should be managed as renewable natural resources that generate economic wealth rather than be managed as places that produce forage for livestock. The major factors that regulate the amount of new wealth generated from rangelands are the quantity of mineral nitrogen available in the soil, and whether the grazing management strategy implemented is beneficial or antagonistic to the ecosystem biogeochemical processes that convert organic nitrogen into mineral nitrogen. Biologically effective grazing management strategies have been developed that beneficially meet the biological requirements of the grass plants and the rhizosphere organisms, and that enhance the microorganism biomass and activity levels sufficiently to convert organic nitrogen into mineral nitrogen at rates greater than 100 pounds per acre.

Native rangeland ecosystems in the Northern Plains that have less than 100 pounds of soil mineral nitrogen per acre do not produce herbage biomass at the biological potential quantities. Rehabilitation of this condition requires minimization of the inhibitory effects on the biogeochemical processes in the rangeland ecosystems caused by deficiencies in necessary elements, principally mineral nitrogen.

Growth of herbage biomass by rangeland grasses requires the essential major elements of carbon, hydrogen, and nitrogen in the presence of sunlight (Manske 2007, 2009d). Radiant energy from the sun is not limiting on rangelands even with about 30% cloud cover, except under the shade of taller shrubs. The source of carbon for plant growth is atmospheric carbon dioxide (CO_2) which composes about 0.03% of the gasses in the atmosphere, exists at concentrations of around 370 ppm, and is not limiting on rangelands. The hydrogen comes from soil water (H_20) absorbed through the roots and distributed throughout the plant within the xylem vascular tissue. Water has been deficient on western North Dakota rangelands at a long-term frequency of 32.7% of the 6.0 month perennial plant growing season from mid April to mid October during the 118 year period, 1892 to 2009 (Manske et al. 2010). Water is a necessary requirement for plant growth and has a dominant role in physiological processes, however, water does not limit herbage production on rangeland ecosystems to the extent that mineral nitrogen availability does (Wight and Black 1972). Deficiencies in mineral nitrogen limit herbage production more often than water in temperate grasslands (Tilman 1990). The source of nitrogen for plant growth on rangelands is mineral nitrogen (NO_3, NH_4) converted from soil organic nitrogen by rhizosphere organisms. The rate of mineralization of soil organic nitrogen into mineral nitrogen is dependant on the rhizosphere volume and microorganism biomass (Gorder, Manske, and Stroh 2004). The quantity of soil mineral nitrogen available at any point during the growing season is the net difference between the variable effects from the two opposing processes of immobilization and mineralization of soil nitrogen (Whitman 1975, Goetz 1975, Manske 2009e). These processes take place simultaneously with plant growth, dieback, and decomposition. Immobilization occurs when autotrophic plants and soil microorganisms absorb mineral nitrogen and build organic nitrogen compounds. Mineralization occurs when complex immobilized organic nitrogen compounds are simplified by processes of the rhizosphere microorganisms to form mineral nitrogen. Available soil mineral nitrogen is the major limiting factor of herbage growth on native rangeland ecosystems (Wight and Black 1979). A minimum rate of mineralization that supplies 100 pounds of mineral nitrogen per acre is required to sustain herbage production at biological potential levels on rangelands (Wight and Black 1972).

Soil mineral nitrogen available at the threshold quantity of 100 lbs/ac is required for activation of three ecological biogeochemical processes important for rangeland grass production. 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. Manske (2010a, 2010b) found evidence that two defoliation resistance mechanisms (Manske 1999, 2007) had threshold requirements for activation at 100 lbs/ac of mineral nitrogen.

Wight and Black (1972) found that precipitation use efficiency of rangeland grasses improved when soil mineral nitrogen was available at quantities greater than 100 lbs/ac. The inhibitory deficiencies of mineral nitrogen on rangelands 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 rangeland ecosystems that had greater than 100 lbs/ac of mineral nitrogen and did not have mineral nitrogen deficiencies (Wight and Black 1979). The quantity of herbage biomass production on rangeland ecosystems that have greater than 100 lbs/ac soil mineral nitrogen will be about double the quantity of herbage biomass production on rangeland ecosystems that have less than 100 lbs/ac soil mineral nitrogen, even during periods of water deficiency.

Manske (2010a, 2010b) found that partial defoliation of grass tillers at phenological growth stages between the three and a half new leaf stage and the flower (anthesis) stage activated the compensatory physiological processes (McNaughton 1979, 1983; Briske 1991) within grass plants that enabled partially defoliated grass tillers to rapidly and completely replace the leaf material removed by grazing, and activated the asexual processes of vegetative reproduction (Mueller and Richards 1986, Richards et al. 1988, Murphy and Briske 1992, Briske and Richards 1994, 1995) that produced secondary tillers from axillary buds in rangeland ecosystems that had soil mineral nitrogen available at quantities greater than 100 lbs/ac, however, the same defoliation treatments did not activate the defoliation resistance mechanisms of grass plants in rangeland ecosystems that had soil mineral nitrogen available at quantities less than 100 lbs/ac. Inhibitory mineral nitrogen deficiencies exist in rangeland ecosystems that have soil mineral nitrogen available at less than 100 lbs/ac and mineral nitrogen deficiencies do not occur in rangeland ecosystems that have soil mineral nitrogen available at 100 lbs/ac or greater (Wight and Black 1972, 1979; Manske 2010a, 2010b).

Full activation of the biogeochemical processes that improve water use efficiency in grass plants, that enable grass tillers to replace leaf material at greater amounts than removed by grazing, and that vegetatively reproduce secondary tillers occurs at biological potential rates only on rangeland ecosystems that have 100 lbs/ac or greater of soil mineral nitrogen available. As a result of full activation of these three processes, grass plants on rangeland ecosystems that have mineral nitrogen at 100 lbs/ac or greater are able to produce greater quantities of herbage per inch of precipitation received, recover rapidly from the effects of grazing and completely replace lost leaf material, produce greater vegetative tiller densities, and produce greater cow and calf weight on less land area than grass plants on rangeland ecosystems that have less than 100 lbs/ac soil mineral nitrogen available.

Since the early portions of the 20th century, the low herbage biomass production observed on native rangelands managed with traditional grazing practices has generally been accepted to be caused by the low levels of available soil mineral nitrogen in the ecosystem (Goetz 1984). The development of management practices that raise the quantity of soil mineral nitrogen in native rangeland ecosystems has been considered to be hugely important for increasing herbage biomass quantity and quality. Major research projects that related to some aspect of increasing soil mineral nitrogen in rangeland ecosystems have been conducted at the Dickinson Research Extension Center from 1956 through 2010. Numerous scientific endeavors to elevate the levels of soil mineral nitrogen on rangelands with the agronomical practices of nitrogen fertilization (Manske 2009e) and of interseeding alfalfa (Manske 2005) were conducted and extensively researched on the Northern Plains between 1951 and 2004 (Manske 2005, 2009e).

Application of nitrogen fertilizer to native rangeland did not solve the problems related to low soil mineral nitrogen. Nitrogen fertilization on degraded rangeland resulted in a small increase in production of herbage biomass per pound of fertilizer nitrogen, and in a short-term shift in plant species composition with an increase in mid cool season grasses and a decrease in short warm season grasses (Manske 2009e). Initially, these desired changes were considered to be beneficial (Manske 2009d). However, reevaluations 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 the native plant community (Manske 2010c). With the reduction of short warm season grasses, live plant basal cover decreased, exposing greater amounts of soil to higher levels of solar radiation and erosion (Goetz et al. 1978). These large areas of open spaces became ideal invasion sites for undesirable plants resulting in the long-term plant species composition shift to a replacement community of domesticated and introduced mid cool season grasses and in the removal of nearly all of the native plant species (Manske 2009a, 2010c).

Interseeding alfalfa into native rangeland did not solve the problems related to low soil mineral nitrogen. The demand on the existing low levels of soil mineral nitrogen in rangeland ecosystems increased with the introduction of alfalfa because almost all of the alfalfa plant nitrogen needs 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 (Manske 2004b). As a result of the low amounts of available mineral nitrogen, the interseeded alfalfa plants had slower rates of growth and higher rates of mortality then alfalfa plants solid seeded into cropland (Manske 2005). Furthermore, the alfalfa plants interseeded into rangeland depleted the soil water levels within a 5 foot radius of each crown an average of 35% below ambient soil water levels causing water stress conditions in the surrounding grass plants and, subsequently, reducing grass herbage biomass production (Manske 2004a, 2005).

Management of rangelands with agronomic principles did not effectively improve ecosystem nitrogen cycling processes and did not solve the problems related to low soil mineral nitrogen. However, the accumulation of scientific information gained from these extensive projects has provided insightful understanding into the complexity of the nitrogen cycle and plant growth in native rangeland ecosystems and contributed a substantial foundation of knowledge from which further progress developed. Identification of the defoliation resistance mechanisms and the biogeochemical processes associated with perennial grass plants and rhizosphere organisms on grassland ecosystems was the next set of essential scientific information needed. The missing factor in achieving healthy productive grasslands at that point was the development of an effective management strategy that could activate these beneficial mechanisms. The emphasis of later research projects was transferred to management of rangelands with ecological principles that progressed into the successful development of a biologically effective grazing strategy that increased soil mineral nitrogen above the threshold quantity of 100 pounds per acre (Manske 1999, 2007, 2008).

Rangeland soils are not deficient of nitrogen. Most of the nitrogen has been immobilized in the soil as organic nitrogen (Legg 1975). The organic nitrogen must be converted into mineral nitrogen in order for soil nitrogen to be available to rangeland plants. The quantity of available mineral nitrogen in rangeland ecosystem soils is dependant on the rate of mineralization of soil organic nitrogen by rhizosphere organisms. The larger the rhizosphere volume and microorganism biomass, the greater the quantity of soil mineral nitrogen converted (Coleman et al. 1983, Ingham et al. 1985). Rhizosphere volume and microorganism biomass are limited by access to carbon and energy from simple carbohydrates because the primary microflora trophic levels (bacteria and endomycorrhizal fungi) in the rhizosphere lack chlorophyll and have low carbon (energy) content (Anderson et al. 1981, Curl and Truelove 1986, Whipps 1990). Healthy grass plants capture and fix carbon during photosynthesis and produce carbohydrates in quantities greater than the amount needed for tiller growth and development (Coyne et al. 1995). Partial defoliation of grass tillers that removes about 25% to 33% of the aboveground leaf material at vegetative phenological growth stages between the three and a half new leaf stage and the flower (anthesis) stage (Manske 2007, 2009c) by large grazing herbivores causes greater quantities of exudated material 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 causes greater rates of mineralization of soil organic nitrogen and results in greater quantities of available mineral nitrogen (Coleman et al. 1983, Clarholm 1985, Klein et al. 1988, Burrows and Pfleger 2002, Rillig et al. 2002, Bird et al. 2002, Driver et al. 2005). The twice-over rotation grazing management system is the biologically effective management strategy that is coordinated with grass phenological growth stages and meets the biological requirements of the perennial grass plants and rhizosphere organisms and that increases rhizosphere activity to mineralize nitrogen at quantities greater than 100 lbs/ac (Manske 1999, 2007, 2010b)

Rangeland ecosystems managed with traditional grazing practices have inhibitory mineral nitrogen deficiencies. Traditional seasonlong grazing practices have soil mineral nitrogen available at low quantities ranging between 59 lbs/ac during mid July (Wight and Black 1972) and 77 lbs/ac during late June (Manske 2010b), and the popular deferred grazing practice has soil mineral nitrogen available at the very low quantity of 31 lbs/ac during mid July (Manske 2008) (table 1).

The rhizosphere organisms on rangeland ecosystems that have less than 100 lbs/ac soil mineral nitrogen available amass in number for about three growing seasons after the biologically effective partial defoliation grazing methods are initiated before the microorganism biomass and activity levels are enhanced sufficiently to be able to mineralize soil organic nitrogen at rates that supply greater than 100 pounds of soil mineral nitrogen per acre. Mineralization rates that have been reached through the biologically effective stimulation grazing methods have ranged between 164 lbs/ac and 199 lbs/ac soil mineral nitrogen available in the top 1 foot of soil during late June (Manske 2008) (table 1). Rhizosphere organisms require elevated quantities of simple carbohydrates exudated from the roots of perennial grass plants annually defoliated by large grazing herbivores removing about 25% to 33% of the aboveground leaf material during the vegetative phenological growth stages between the three and a half new leaf stage and the flower stage to maintain mineralization rates at greater than 100 lbs/ac soil mineral nitrogen.

The threshold quantity of soil mineral nitrogen at 100 lbs/ac or greater during mid to late June is required to fully activate three significant biogeochemical processes; the water use efficiency processes, the compensatory physiological processes, and the asexual vegetative reproduction processes in rangeland grass plants. These important findings give rangeland managers the first quantitative standard from which the condition of an ecosystem can be judged as healthy or unhealthy. In the near future, the health and ecological status of any rangeland ecosystem will be quantitatively evaluated by a simple measurement of available soil mineral nitrogen. Rangeland ecosystems that have soil mineral nitrogen available at quantities greater than 100 lbs/ac are functioning above biological potential production capacity and rangeland ecosystems that have soil mineral nitrogen available at quantities less than 100 lbs/ac have a soil mineral nitrogen deficiency and are functioning below biological potential production capacity.

The quantities of soil mineral nitrogen available at other time periods during the entire perennial grass growing season, mid April to mid October, need to be determined for grazed rangeland ecosystems in the Northern Plains. It is unlikely that the quantity of soil mineral nitrogen is a stationary value through the growing season. Soil mineral nitrogen in native rangeland ecosystems is most likely available in dynamic cycles with peaks and valleys during the growing season (Goetz 1975). The threshold quantity of 100 lbs/ac most likely represents the minimum amount of soil mineral nitrogen available in a healthy fully functioning rangeland ecosystem at any time during the growing season.

Rangelands in the Northern Plains have been perceived to have low productivity levels because the economic returns from livestock agriculture have usually been low. Low returns from rangelands have not been caused by inherent negative characteristics of rangeland ecosystems but have been caused by management induced problems. Low productivity on rangelands has resulted from the low quantity of available mineral nitrogen that was caused by the antagonistic effects from traditional grazing management practices on the rhizosphere organisms and the biogeochemical processes reducing the amount of organic nitrogen converted into mineral nitrogen. Beneficial biologically effective grazing management strategies stimulate rhizosphere organism activities and ecosystem biogeochemical processes that increase the quantity of available soil mineral nitrogen to exceed 100 pounds per acre. Soil mineral nitrogen available at 100 lbs/ac or greater results in increased herbage and forage nutrient production, improved cow and calf performance, improved efficiency of forage nutrient capture, and improved efficiency of the conversion of forage nutrients into saleable commodities of livestock weight which are essential for the beef production industry to achieve actual reductions in forage feed costs and increases in the quantity of new wealth generated from rangelands.

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Table 1. Soil mineral nitrogen quantity and rhizosphere volume.

Grazing Management Practice	Mineral Nitrogen lbs/ac-ft	Rhizosphere Volume ft^3/ac-ft
4.5-5.0 month Deferred	31	-
Traditional Seasonlong	59	-
6.0 month Seasonlong	62	50
4.5 month Seasonlong	77	68
Twice-over Rotation	178	227
1st pasture grazed	199	-
2nd pasture grazed	164	-
3rd pasture grazed	171	-

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