Evaluation of Plant Species Shift on Fertilized Native Rangeland

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Nitrogen fertilization of native rangeland results in a plant species composition shift with an increase in mid cool season grasses and a decrease in short warm season grasses and these changes have been shown to occur from 30 and 90 lbs N/ac annually applied in fall and monitored for 7 years (Rogler and Lorenz 1957), from 33, 67, and 100 lbs N/ac annually applied to two range sites in spring and monitored for 2 years (Whitman 1963), from 33, 67, and 100 lbs N/ac annually applied to four range sites in spring and monitored for 6 years (Whitman 1969, Goetz 1969), from 30, 60, 120, 240, and 480 lbs N/ac applied over 1 year, 3 years, and 6 years in spring and monitored for 6 years (Power and Alessi 1971), from 40, 80, and 160 lbs N/ac annually applied with and without phosphate in fall and monitored for 8 years (Lorenz and Rogler 1972), from 100 lbs N/ac annually applied for 3 years in fall and monitored for 15 years (Taylor 1976), from 67 and 100 lbs N/ac annually and biennially applied in spring and 200, 300, and 400 lbs N/ac applied one time and monitored for 8 years (Whitman 1978, Goetz et al. 1978), and from low rates of less than 100 lbs N/ac annually applied in spring and high rates of greater than 100 lbs N/ac applied one time and monitored for 10 years (Wight and Black 1979). This shift in plant species composition was, at first, considered to be a beneficial change and a process to restore the natural balance in the botanical species composition of the Northern Plains mixed grass prairie.

The disruption of the natural species composition was caused during the homestead period between 1900 and 1936 by excessively heavy grazing with stocking rates greater than 60% heavier than the biological carrying capacity (Whitman et al. 1943). The resulting deterioration in the Northern Plains mixed grass prairie caused a decrease in herbage biomass production and a disproportional reduction of mid cool season grass species, such as western wheatgrass, and leaving a predominance of short warm season grass species, such as blue grama.

Heavy grazing damages grass species with long shoot tillers to a greater extent than grass species with short shoot tillers. Grass species with long shoots elevate the apical meristem a short distance above ground level by internode elongation while still in the vegetative phase (Dahl 1995) exposing the elevated apical meristem to removal by grazing prior to flowering. Grass species with short shoots do not produce significant internode elongation during vegetative growth and the apical meristem remains below grazing or cutting height until the flower stalk elongates during the sexual reproductive phase (Dahl 1995). Grass species with long shoots are nearly always decreased at greater rates than grass species with short shoots in pastures that are repeatedly grazed heavily (Branson 1953).

Application of nitrogen fertilizer to native rangeland in spring or fall, at low rates, high rates, annually, biennially, or one time all cause a shift in species composition with an increase in mid cool season grasses and a decrease in short warm season grasses. These multiple variables, however, do affect the rates of change differently and the shift in plant species composition does not occur at the same rate under different conditions. Cultural management practices of nitrogen fertilization that seemed to restore the natural species composition balance and appeared to correct existing problems were initially considered to be beneficial.

However, Goetz et al. (1978) found several undesirable aspects related to the changes in plant species composition that have implications of adverse consequences for mixed grass prairie communities. Detrimental complications could develop from synthetically induced changes in plant species because the increasing mid cool season grasses were primarily single stalked, low-cover, plants and the decreasing short warm season grasses were primarily multiple stemmed, high-cover, plants and the shift in plant species would cause a decrease in basal cover and a reduction in live plant material covering the soil and would open an otherwise closed community. The resulting reductions in ground cover would expose greater amounts of soil to erosion and to higher levels of solar radiation, and would create larger areas of open spaces available for potential invasion by undesirable perennial forbs, domesticated cool season grasses, and introduced annual and perennial grasses.

Eventhough, the nitrogen fertilization plot studies conducted in the Northern Plains from the early 1950's to the mid 1980's were comparatively long with 6 to 10 years of monitoring data, none of the studies were conducted long enough to fully document the undesirable changes proposed by Goetz et al. 1978. Taylor (1976) conducted a study for 15 years and found that residual effects from nitrogen fertilization of native rangeland were still occurring 12 years after the treatments had stopped.

This report uses compiled vegetation data from four studies to follow the plant species composition changes in a nitrogen fertilized mixed grass prairie community during 33 years from 1972 to 2004 and corroborates the adverse implications of nitrogen fertilization in native rangeland that were hypothesized to occur by Goetz et al. 1978.

Procedure

The changes in plant species composition evaluated during this investigation occurred in the mixed grass prairie communities of the unfertilized and nitrogen fertilized pastures of the fertilization of native rangeland grazing study. The research pastures were located on the SW½, sec. 23, T. 140 N., R. 97 W., at the Dickinson Research Extension Center. The native rangeland plant community was strongly rolling upland mixed grass prairie. The soils were Vebar, Parshall, and Flasher fine sandy loams. The control pasture was 18 acres of untreated native rangeland. The fertilized pasture was 12 acres of native rangeland fertilized annually with ammonium nitrate fertilizer (33-0-0) broadcast applied in granular form at a rate of 50 lbs N/ac in early spring, usually around early to mid April, for eleven years from 1972 to 1982. The growing season of 1982 was the last year of fertilizer application.

The unfertilized and fertilized native rangeland pastures were grazed by yearling steers from 1972 to 1976 and grazed by cow-calf pairs from 1977 to 1982 during mid June to late August or early September. The fertilized pasture grazing project was not conducted in 1983. A two grazing period study was conducted from 1984 to 1988 on the unfertilized pasture. The unfertilized pasture was grazed by cow-calf pairs for two periods per year with the first period during early to mid June and the second period during mid July to mid August. The fertilized pasture was not fertilized after 1982 and was grazed by cow-calf pairs from 1984 to 1988 one period during mid June to late August or early September. Grazing studies were terminated at this location and the pastures were grazed by cattle that were not in research projects. The pastures were used from 1989 to 2004 for one period usually during early June to late August.

Aboveground herbage biomass production was sampled on the unfertilized and fertilized native rangeland pastures by the clipping method from inside and outside exclosure cages in 1972 to 1982, on the unfertilized pasture from inside and outside exclosure cages in 1984 to 1988, and on the unfertilized and fertilized pastures in 1997 to 2004. The exclosures were steel wire quonset type cages measuring 3 X 7 foot. During 1972 to 1988, the exclosures were distributed in a systematic grid with an average of 20 exclosures per pasture. The exclosure cages were moved within the respective grids every spring. All of the herbage samples were oven dried and weighed. During 1972 to 1976, dry aboveground herbage biomass was sampled by hand clipping to ground level from 2.5 X 5.0 foot (0.75 X 1.5 meter) heavy steel frames with one clip per year at the end of the grazing period during mid August to mid September. The plant material was not separated into categories. During 1977 to 1981, dry aboveground herbage biomass was sampled by hand clipping to ground level from 0.82 X 3.28 foot (0.25 X 1.0 meter) light weight steel frames with two clippings per year at the beginning and end of the grazing period with the first clip during mid June to mid July and the second clip during late July to mid August. The plant material was not separated into categories. During 1982 to 1988, dry aboveground herbage biomass was sampled by hand clipping to ground level from 0.82 X 3.28 foot (0.25 X 1.0 meter) light weight steel frames with four clippings per year with the first clip during early to mid June, the second clip during mid June to mid July, the third clip during mid July to mid August, and the fourth clip during mid August to mid September. The plant material was separated into five categories: warm season grasses, cool season grasses, sedges, introduced grasses, and forbs. An additional clip was conducted during mid May in 1982. Herbage weight data were not collected in 1983.

Herbage samples were not collected between 1989 and 1996. During 1997 to 2004, the unfertilized and fertilized native rangeland pastures were each separated into three equal sized replicated sample zones; west, middle, and east. Dry aboveground herbage biomass was sampled by hand clipping to ground level from three to five 0.82 X 3.28 foot (0.25 X 1.0 meter) light weight steel frames from each of the three replicated zones with one clip per year during late June to mid August. The plant material was separated into five categories: warm season grasses, cool season grasses, sedges, introduced grasses, and forbs. The exclosure cages had been moved to other research pastures and the sites clipped were areas with no or low herbage removed by grazing livestock. Herbage weight data were not collected in 2003.

Quantitative species composition was determined by percent basal cover sampled with the ten-pin point frame method during the period of mid July to mid August, on the unfertilized and fertilized pastures in 1982, on the unfertilized pasture in 1985 to 1988, and on the unfertilized and fertilized pastures in 1998-2004.

Results

The precipitation during the growing seasons of 1972 to 1976 was normal or greater than normal (table 1). During 1972, 1973, 1974, 1975, and 1976, 18.57 inches (137.05% of LTM), 11.83 inches (87.31% of LTM), 12.45 inches (91.88% of LTM), 15.26 inches (112.62% of LTM), and 10.84 inches (80.00% of LTM) of precipitation were received, respectively. Perennial plants were under water stress conditions during September, 1972; July, August, and October, 1973; July, August, September, and October, 1974; July, August, and September, 1975; and July and August, 1976 (Manske 2009).

The precipitation during the growing seasons of 1977 to 1982 was normal or greater than normal (table 1). During 1977, 1978, 1979, 1980, 1981, and 1982, 18.65 inches (137.64% of LTM), 15.17 inches (111.96% of LTM), 11.12 inches (82.07% of LTM), 10.73 inches (79.19% of LTM), 14.27 inches (105.31% of LTM), and 22.53 inches (166.27% of LTM) of precipitation were received, respectively. Perennial plants were under water stress conditions during April and July, 1977; October, 1978; October, 1979; April, May, July, and September, 1980; and July and October, 1981. The April through July precipitation received in 1980 was 44.5% of the LTM causing drought conditions, and August and October of 1980 were wet months. Perennial plants did not experience water stress conditions during 1982 (Manske 2009).

The precipitation during the growing seasons of 1997 to 2004 was normal or greater than normal (table 2). During 1997, 1998, 1999, 2000, 2001, 2002, 2003, and 2004, 14.74 inches (108.78% of LTM), 20.51 inches (151.37% of LTM), 14.20 inches (104.80% of LTM), 11.91 inches (87.90% of LTM), 17.74 inches (130.92% of LTM), 15.47 inches (114.17% of LTM), 11.45 inches (84.50% of LTM), and 10.26 inches (75.77% of LTM) of precipitation were received, respectively. Perennial plants were under water stress conditions during August and September, 1997; July and October, 1999; August and September, 2000; August and October, 2001; September, 2002; July and August, 2003; and June and August, 2004. The April through August precipitation received in 2004 was 52.8% of the LTM causing mild drought conditions. Perennial plants did not experience water stress conditions during 1998 (Manske 2009).

Trial I (1972-1976)

The unfertilized and fertilized pasture herbage weight samples collected in 1972 to 1976 were clipped to ground level from inside and outside exclosure cages one time per growing season during the clip period of mid August to mid September. Some previous years standing dead were included in the samples collected from inside the exclosure cages. The herbage samples were not separated into categories. The reported data were mean total ungrazed herbage from the one clip period.

Mean aboveground total ungrazed herbage weight during 1972 to 1976 was 2676.60 lbs per acre on the unfertilized pasture and was 4010.00 lbs per acre on the fertilized pasture during the clip period of mid August to mid September (table 3). The total ungrazed herbage weight on the fertilized pasture was 49.8% greater than, but not significantly different ($P<0.05$) from, the total ungrazed herbage weight on the unfertilized native rangeland pasture.

Trial II (1977-1982)

The unfertilized and fertilized pasture herbage weight samples collected in 1977 to 1981 were clipped to ground level from inside and outside exclosure cages two times per growing season during the clip period of mid June to mid July and during the clip period of mid July to mid August. The herbage samples were not separated into categories. The reported data were mean total ungrazed herbage from the two clip periods.

Mean aboveground total ungrazed herbage weight during 1977 to 1979 and 1981 to 1982 was 1733.72 lbs per acre on the unfertilized pasture and was 2623.95 lbs per acre on the fertilized pasture during the two grazing season clip periods between early June and mid September (table 3). The mean total ungrazed herbage weight on the fertilized pasture was 51.3% greater than, but not significantly different ($P<0.05$) from, the mean total ungrazed herbage weight on the unfertilized native rangeland pasture. In 1980, drought conditions occurred from April through July with only 44.5% of the LTM precipitation received. The ungrazed herbage samples were collected 7 and 23 July after 2.67 inches of precipitation was received in June. Mean aboveground total ungrazed herbage weight during 1980 was 1296.45 lbs per acre on the unfertilized pasture and was 1386.85 lbs per acre on the fertilized pasture (table 3). The mean total ungrazed herbage weight on the fertilized pasture was 7.0% greater than, but not significantly different ($P<0.05$) from, the total ungrazed herbage weight on the unfertilized pasture.

The unfertilized and fertilized pasture herbage weight samples collected in 1982 were clipped to ground level from inside and outside exclosure cages five times per growing season. The first clip was during mid May before grasses were phenologically ready for grazing. After grasses were phenologically ready for grazing, the second clip was during the clip period of early to mid June, the third clip was during the clip period of mid June to mid July, the fourth clip was during the clip period of mid July to mid August, and the fifth clip was during the clip period of mid August to mid September. The herbage was separated into five categories: warm season grasses, cool season grasses, sedges, introduced and domesticated grasses, and forbs. The reported data was mean ungrazed herbage for each category and for the total yield of all categories from the four grazing season clip periods between early June and mid September.

The growing season of 1982 was the eleventh and last year with an application of 50 lbs N/ac on the fertilized native rangeland pasture. The effects from 11 years of fertilization on native rangeland vegetation were determined from herbage weight clipped during 5 periodic dates and separated into categories and from plant species composition determined by basal cover.

Cool season grasses on the unfertilized and fertilized pastures gained herbage weight during May, June, and July, and then lost aboveground biomass during August and September (table 4). Mean cool season grass herbage weight during the four grazing season clip periods between early June and mid September was 898.28 lbs per acre, composing 46.99%, on the unfertilized pasture and was 2392.55 lbs per acre, composing 65.41%, on the fertilized pasture. Mean cool season herbage weight on the fertilized pasture was 166.3% greater than mean cool season herbage weight on the unfertilized pasture. Mean sedge herbage weight on the unfertilized pasture was 281.90 lbs per acre, composing 14.75%, and was 236.70 lbs per acre, composing 6.47%, on the fertilized pasture. Mean sedge herbage weight on the fertilized pasture was 16.0% lower than that on the unfertilized pasture (tables 6 and 7).

Warm season grasses, total native grasses, and total yield on the unfertilized pasture gained herbage weight during May, June, July, and August, and lost aboveground biomass during September. Warm season grasses, total native grasses, and total yield on the fertilized pasture gained herbage weight during May, June, and July, and lost aboveground biomass during August and September (table 4). Mean warm season grass herbage weight during the four grazing season clip periods was 517.15 lbs per acre, composing 27.05%, on the unfertilized pasture and was 147.40 lbs per acre, composing 4.03%, on the fertilized pasture. Mean warm season grass herbage weight on the fertilized pasture was 71.5% lower than mean warm season grass herbage weight on the unfertilized pasture (tables 6 and 7).

Forbs on the unfertilized pasture gained herbage weight during May, June, and July, and lost aboveground biomass during August and September. Forbs on the fertilized pasture gained herbage weight during May, June, July, and August, and lost aboveground biomass during September (table 4). Mean forb herbage weight during the four grazing season clip periods was 214.27 lbs per acre, composing 11.21%, on the unfertilized pasture and was 364.25 lbs per acre, composing 9.96%, on the fertilized pasture. Almost all of the forb herbage weight on the fertilized pasture was fringed sage. Mean forb herbage weight on the fertilized pasture was 70.0% greater than mean forb herbage weight on the unfertilized pasture (tables 6 and 7).

Mean total native grass herbage weight on the fertilized pasture was 63.6% greater than mean total native grass herbage weight on the unfertilized pasture. Mean total yield herbage weight was 91.4% greater on the fertilized pasture than on the unfertilized pasture. The greater production of herbage weight on the fertilized pasture resulted from the increase in cool season grass and forb herbage weight and from the additional 517.05 lbs per acre of herbage weight produced by introduced and domesticated grasses that were not measured on the unfertilized pasture (tables 4 and 6).

Mean percent composition of herbage weight on the fertilized pasture was 39.2% greater for cool season grasses, and was 85.1% lower for warm season grasses, 56.1% lower for sedges, and 11.2%

lower for forbs than the percent composition of herbage weight of the respective categories on the unfertilized pasture (tables 5 and 7). Herbage weight of introduced and domesticated grasses, composed 14.1% of the mean total herbage yield on the fertilized pasture.

Mean percent total basal cover of the plant community during 1982 was 22.81% on the unfertilized pasture and was 17.47% on the fertilized pasture. Total basal cover on the fertilized pasture was 23.4% lower than total basal cover on the unfertilized pasture (table 8). Warm season grass basal cover was 9.94% on the unfertilized pasture and was 3.20% on the fertilized pasture. Warm season grass basal cover on the fertilized pasture was 67.8% lower than that on the unfertilized pasture. Basal cover of mid warm season grasses, primarily little bluestem and sideoats grama, had decreased 95.3% and basal cover of short warm season grasses, primarily blue grama, had decreased 65.9% on the fertilized pasture (table 13). Cool season grass basal cover was 4.47% on the unfertilized pasture and was 6.27% on the fertilized pasture. Cool season grass basal cover on the fertilized pasture was 40.3% greater than that on the unfertilized pasture. Basal cover of mid cool season grasses, primarily western wheatgrass and green needlegrass, had increased 94.3% and basal cover of short cool season grasses, primarily prairie Junegrass, had decreased 26.5% on the fertilized pasture (table 13). Sedge basal cover on the unfertilized pasture was 6.64% and was 5.70% on the fertilized pasture. Sedge basal cover on the fertilized pasture was 14.2% lower than that on the unfertilized pasture. Total native grass basal cover on the unfertilized pasture was 21.05% and was 15.17% on the fertilized pasture. Total native grass basal cover on the fertilized pasture was 27.9% lower than that on the unfertilized pasture. Domesticated grass basal cover was 0.36% on the unfertilized pasture and was 1.96% on the fertilized pasture. Domesticated grass basal cover on the fertilized pasture was 444.4% greater than that on the unfertilized pasture. The domesticated grasses were crested wheatgrass with a basal cover of 0.67% and smooth bromegrass with a basal cover of 0.63%. The introduced grasses were Kentucky bluegrass and Canada bluegrass with a combined basal cover of 0.66% (table 13). Forb basal cover on the unfertilized pasture was 1.40% and was 0.34% on the fertilized pasture. Forb basal cover on the fertilized pasture was 75.7% lower than that on the unfertilized pasture (table 8). The typical shift in plant species composition with an increase in mid cool season grasses and a decrease in short warm season grasses occurred as a result of eleven years of 50 lbs N/ac applied each spring. Total basal cover decreased 23.4% on the fertilized pasture because the increasing plants, consisting of native mid cool season grasses, domesticated mid cool season grasses, and introduced mid cool season grasses, were single stalked, low-cover plants and the decreasing plants, consisting of native mid and short warm season grasses, native short cool season grasses, and native upland sedges, were multiple stemmed, high-cover plants.

Trial III (1984-1988)

Herbage weight and basal cover samples were not collected on the fertilized pasture during 1984 to 1988. The unfertilized pasture herbage weight samples collected in 1984 to 1988 were clipped to ground level from inside and outside exclosure cages four times per growing season. The first clip was during the clip period of early to mid June, the second clip was during the clip period of mid June to mid July, the third clip was during the clip period of mid July to mid August, and the fourth clip was during the clip period of mid August to mid September. The herbage was separated into five categories: warm season grasses, cool season grasses, sedges, introduced and domesticated grasses, and forbs. The reported data for 1984 was mean ungrazed herbage for each category and for the total yield of all categories from two clip periods; the clip period of mid June to mid July, and the clip period of mid August and mid September. The reported data for 1985 to 1988 was mean ungrazed herbage for each category and for the total yield of all categories from the four grazing season clip periods conducted between early June and mid September.

Mean aboveground total ungrazed herbage weight during 1984 to 1987 was 1429.72 lbs per acre on the unfertilized pasture during the growing season periods between early June and mid September (tables 3 and 6). Mean warm season herbage weight was 293.45 lbs per acre and composed 20.3% of the total herbage weight. Mean cool season herbage weight was 416.35 lbs per acre and composed 29.1% of the total herbage weight. Mean sedge herbage weight was 581.99 lbs per acre and composed 41.1% of the total herbage weight. Mean total native grass herbage weight was 1291.78 lbs per acre and composed 90.5% of the total herbage weight. Mean forb herbage weight was 137.94 lbs per acre and composed 9.5% of the total herbage weight (tables 6 and 7). In 1988, severe drought conditions occurred during the entire growing season with only 48.4% of the LTM precipitation received from April through October. Mean aboveground total ungrazed herbage weight in 1988 was 451.23 lbs per acre on the unfertilized pasture during the growing season periods between early June and mid September (tables 3 and 6). Mean warm season herbage weight was 92.03 lbs per acre and composed 20.4% of the total herbage weight. Mean cool season herbage weight was 89.54 lbs per acre and composed 19.8% of the total herbage weight. Mean sedge herbage weight was 208.58 lbs per acre and composed 46.2% of the total herbage weight. Mean total native grass herbage weight was 390.15 lbs per acre and composed 86.5% of the total herbage weight. Mean forb herbage weight was 61.08 lbs per acre and composed 13.5% of the total herbage weight (tables 6 and 7).

Mean total basal cover during 1985 to 1987 was 30.59% on the unfertilized pasture (table 8). Mean warm season grass basal cover was 9.95%. Mean cool season grass basal cover was 6.20%. Mean sedge basal cover was 10.47%. Mean total native grass basal cover was 26.62%. Mean forb basal cover was 3.94% (table 8).

Mean total basal cover during the 1988 drought conditions was 26.83% on the unfertilized pasture (table 8). Mean warm season grass basal cover was 8.51%. Mean cool season grass basal cover was 5.21%. Mean sedge basal cover was 7.88%. Mean total native grass basal cover was 21.60%. Mean forb basal cover was 5.23% (table 8).

Trial IV (1997-2004)

The unfertilized and fertilized pasture herbage weight samples collected in 1997 to 2002 and 2004 were clipped to ground level one time per growing season during late June to mid August. The herbage was separated into five categories: warm season grasses, cool season grasses, sedges, introduced and domesticated grasses, and forbs. The pastures were grazed and the clipped herbage samples were collected from ungrazed or lightly grazed areas. The reported data were mean ungrazed herbage or lightly grazed herbage for each category and for the total yield of all categories from the one clip period on each of the three replicated pasture zones.

Mean aboveground total yield herbage weight during 1997 to 1999 and 2001 to 2002 was 1348.47 lbs per acre on the unfertilized pasture and was 2288.09 lbs per acre on the fertilized pasture during the growing season period of early June to mid August (tables 9 and 10). The total herbage weight on the fertilized pasture was 69.7% greater than, and significantly different ($P<0.05$) from, the total herbage weight on the unfertilized pasture. Mean warm season grass herbage weight was 236.77 lbs per acre, composing 18.96%, on the unfertilized pasture and was 71.31 lbs per acre, composing 3.39%, on the fertilized pasture. Warm season grass herbage weight on the fertilized pasture was 69.9% lower than, and significantly different ($P<0.05$) from, mean warm season grass herbage weight on the unfertilized pasture. Mean cool season grass herbage weight was 453.28 lbs per acre, composing 34.74%, on the unfertilized pasture and was 125.74 lbs per acre, composing 6.12%, on the fertilized pasture. Cool season grass herbage weight on the fertilized pasture was 72.3% lower than, and significantly different ($P<0.05$) from, that on the unfertilized pasture. Mean sedge herbage weight on the unfertilized pasture was 319.79 lbs per acre, composing 22.70%, and was 199.81 lbs per acre, composing 9.33%, on the fertilized pasture and were not significantly different ($P<0.05$). Mean total native grass herbage weight was 1009.84 lbs per acre, composing 76.41%, on the unfertilized pasture and was 396.86 lbs per acre, composing 18.83%, on the fertilized pasture. Total native grass herbage weight on the fertilized pasture was 60.7% lower than, and significantly different ($P<0.05$) from, that on the unfertilized pasture. Mean domesticated grass herbage weight was 108.94 lbs per acre, composing 7.53%, on the unfertilized pasture and was 1785.52 lbs per acre, composing 78.04%, on the fertilized pasture. Domesticated grass herbage weight on the fertilized pasture was 1539.0% greater than, and significantly different ($P<0.05$) from, domesticated grass herbage weight on the unfertilized pasture. Mean forb herbage weight on the unfertilized pasture was 229.68 lbs per acre, composing 16.06%, and was 105.71 lbs per acre, composing 4.90%, on the fertilized pasture and were not significantly different ($P<0.05$) (tables 10 and 11).

Mean percent composition of herbage weight for warm season grass, cool season grass, sedge, total native grass, and forbs were significanly lower ($P<0.05$) on the fertilized pasture than on the unfertilized pasture. Mean percent composition of herbage weight for domesticated grass were significantly greater ($P<0.05$) on the fertilized pasture than on the unfertilized pasture (table 11). The herbage weight samples of 2000 were collected from areas that were more than lightly grazed. In 2004, mild drought conditions occurred from April through August with 52.8% of the LTM precipitation received.

Mean percent total basal cover of the plant community during 1998 to 1999 and 2001 to 2003 was 26.37% on the unfertilized pasture and was

21.96% on the fertilized pasture and were not significantly different (P<0.05) (table 12). Mean warm season grass basal cover was 7.92% on the unfertilized pasture and was 2.56% on the fertilized pasture. Warm season grass basal cover on the fertilized pasture was 67.7% lower than, and significantly different (P<0.05) from, mean warm season grass basal cover on the unfertilized pasture. Basal cover of mid warm season grasses had decreased 80.0% and basal cover of short warm season grasses had decreased 63.5% on the fertilized pasture (table 13). Mean cool season grass basal cover was 5.42% on the unfertilized pasture and was 1.34% on the fertilized pasture. Cool season grass basal cover on the fertilized pasture was 75.3% lower than, and significantly different (P<0.05) from, that on the unfertilized pasture. Basal cover of mid cool season grasses had decreased 66.1% and basal cover of short cool season grasses had decreased 86.9% on the fertilized pasture (table 13). Mean sedge basal cover on the unfertilized pasture was 7.18% and was 4.45% on the fertilized pasture and were not significantly different (P<0.05). Mean total native grass basal cover on the unfertilized pasture was 20.52% and was 8.35% on the fertilized pasture. Total native grass basal cover on the fertilized pasture was 59.3% lower than, and significantly different (P<0.05) from, that on the unfertilized pasture. Mean domesticated grass basal cover was 2.45% on the unfertilized pasture and was 12.39% on the fertilized pasture. Domesticated grass basal cover on the fertilized pasture was 405.7% greater than, and significantly different (P<0.05) from, domesticated grass basal cover on the unfertilized pasture. Basal cover of crested wheatgrass had increased 577.6%, basal cover of smooth bromegrass had increased 568.3%, and basal cover of Kentucky bluegrass and Canada bluegrass had increased 451.5% from their respective basal cover in 1982 (table 13). The introduced and domesticated grasses had back filled 81.7% of the open spaces created in the plant community by the decrease in native grass basal cover on the fertilized pasture. Mean forb basal cover on the unfertilized pasture was 3.40% and was 1.22% on the fertilized pasture. Forb basal cover on the fertilized pasture was 64.1% lower than, and significantly different (P<0.05) from, that on the unfertilized pasture (table 12). The basal cover samples of 2000 were collected from areas that were more than lightly grazed. In 2004, mild drought conditions occurred from April through August with 52.8% of the LTM precipitation received.

Introduced and domesticated grasses are apparently capable of occupying open spaces created by native grass reductions in the plant community when soil mineral nitrogen is readily available. The plant community in the fertilized pasture would be expected to continue to change in plant species composition with a decrease in native warm season grasses, cool season grasses, upland sedges, and prairie forbs and an increase in domesticated and introduced mid cool season grasses until the quantity of applied fertilizer nitrogen was no longer readily available as soil mineral nitrogen. The duration of time that the applied fertilizer nitrogen would remain in the ecosystem could be estimated by determination of the fate of the applied fertilizer nitrogen according to the nitrogen fate percentages developed by Power (1977).

The fate of applied nitrogen fertilizer in native rangeland ecosystems is dependent on various biotic and abiotic factors called nitrogen sinks. Power (1977) determined the nitrogen content in the various sinks of a grazed native mixed grass prairie near Mandan, ND. Power (1977) subtracted the nitrogen content of the unfertilized pasture from the nitrogen content of the fertilized pasture to determine the content and percentage of the applied fertilizer nitrogen in each sink.

The fate of nitrogen as a percent of applied fertilizer determined by Power (1977) is shown in the left column of table 14. Power (1977) determined that 8% or 4.0 lbs per acre of the applied nitrogen was lost from the ecosystem per year. At a constant rate of loss at 4.0 lbs of applied nitrogen per acre per year, the applied nitrogen would be used up in 126.5 years from the last year fertilizer was applied and the ecosystem should be devoid of fertilizer nitrogen sometime during the growing season in the year 2109.

Discussion

Nitrogen fertilization of native rangeland with annual applications of 50 lbs N/ac caused the plant species composition to shift. Pasture fertilization increased total herbage weight 49.8% during 1972 to 1976, and increased mean total herbage weight 51.3% during 1977 to 1982. In 1982, after 11 years of fertilization treatments, total herbage weight had increased 91.4% and the plant species composition had changed greatly. Cool season grass herbage weight had increased 166.3%, composition had increased 39.2%, and basal cover had increased 40.3%. Warm season grass herbage weight had decreased 71.5%, composition had decreased 85.1%, and basal cover had decreased 67.8%. Upland sedge herbage weight had decreased 16.0%, composition had decreased 56.1%, and basal cover had decreased 14.2%. Forb herbage weight had increased 70.0%, composition had decreased 11.2%, and basal cover had decreased 75.4%. The quantity of forb plants and the number of forb species had greatly decreased on the fertilized pasture. A few of the remaining plants were fringed sage that had greatly increased in size and weight. Fringed sage composed around 50% of the forb basal cover and almost all of the forb herbage weight. A small amount of domesticated and introduced mid cool season grasses had encroached into the fertilized pasture by 1982. This plant species intrusion was not recognized as a serious problem at that time because the domesticated and introduced grasses had produced only 517.05 lbs per acre of herbage weight and occupied only 1.96% basal cover.

The residual effects from nitrogen fertilization of native rangeland continued to change the plant species composition for an additional twenty two years after the fertilization treatments had stopped. During 1997 to 2004, the total herbage weight was 69.7% greater on the fertilized pasture than on the unfertilized pasture. However, the composition of the herbage weight had greatly changed; domesticated and introduced grasses composed 78.0%, native grasses composed 17.3%, and forbs composed 4.6% of the total herbage weight. Cool season grass herbage weight had decreased 72.3%, composition had decreased 82.4%, and basal cover had decreased 75.3%. Warm season grass herbage weight had decreased 69.9%, composition had decreased 82.1%, and basal cover had decreased 67.7%. Upland sedge herbage weight had decreased 37.5%, composition had decreased 58.9%, and basal cover had decreased 38.0%. Forb herbage weight had decreased 54.0%, composition had decreased 69.5%, and basal cover had decreased 64.1%. Domesticated and introduced grass herbage weight had increased 1539.0%, composition had increased 936.9%, and basal cover had increased 405.7%. The small encroachment of nonnative grasses had transformed into an overwhelming occupation.

After eleven years of fertilization treatments, native mid cool season grasses had greatly increased in herbage weight and basal cover. Herbage weight the other native grasses had decreased less than the mid cool season grasses had increased. Total native grass herbage weight had increased 63.6%, however, total native grass basal cover had decreased 27.9% in eleven years. Twenty two years after treatments had stopped, native grass herbage weight had decreased 82.7% and basal cover had decreased 60.3%. Fertilization of native rangeland caused native warm season grasses, cool season grasses, and upland sedges to decrease greatly, and after 33 years of plant species composition change, the native grasses only composed 17.3% of the total herbage weight and 38.0% of the total basal cover.

Domesticated and introduced grasses started from zero and increased slowly, and after eleven years of fertilization treatments, domesticated and introduced grasses composed 14.1% of the total herbage weight and composed 11.2% of the total basal cover. Twenty two years after treatments had stopped, domesticated and introduced grass herbage weight had increased 342.5% and basal cover had increased 532.1%. Fertilization of native rangeland caused domesticated and introduced grasses to increase greatly, and after 33 years of plant species composition change, the domesticated and introduced grasses composed 78.0% of the total herbage weight and 56.4% of the total basal cover.

Nitrogen fertilization of native rangeland changed the plant species composition from a mixed grass prairie community of warm season grasses, cool season grasses, upland sedges, and prairie forbs to a community dominated by introduced and domesticated mid cool season grasses in 33 years. The residual effects from nitrogen fertilization continue to change the plant species composition of the fertilized rangeland pasture.

Acknowledgment

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Table 1. Precipitation in inches for growing season months and the annual total precipitation for 1972-1982, Dickinson, North Dakota.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-term mean 1892-2007	1.43	2.34	3.55	2.22	1.73	1.33	0.95	13.55	16.00
1972	1.27	5.09	4.29	2.72	2.90	0.74	1.56	18.57	20.76
% of LTM	88.81	217.52	120.85	122.52	167.63	55.64	164.21	137.05	129.75
1973	3.21	1.30	3.04	0.91	0.47	2.23	0.67	11.83	13.53
% of LTM	224.48	55.56	85.63	40.99	27.17	167.67	70.53	87.31	84.56
1974	2.82	4.15	2.00	1.50	0.90	0.56	0.52	12.45	14.15
% of LTM	197.20	177.35	56.34	67.57	52.02	42.11	54.74	91.88	88.44
1975	4.25	3.34	4.27	0.64	0.54	0.80	1.42	15.26	17.71
% of LTM	297.20	142.74	120.28	28.83	31.21	60.15	149.47	112.62	110.69
1976	2.11	1.42	3.74	0.75	0.40	1.77	0.65	10.84	12.68
% of LTM	147.55	60.68	105.35	33.78	23.12	133.08	68.42	80.00	79.25
1977	0.13	2.60	5.38	1.08	1.52	5.78	2.16	18.65	23.13
% of LTM	9.09	111.11	151.55	48.65	87.86	434.59	227.37	137.64	144.56
1978	1.81	3.99	2.10	2.41	2.01	2.56	0.29	15.17	17.63
% of LTM	126.57	170.51	59.15	108.56	116.18	192.48	30.53	111.96	110.19
1979	1.28	0.91	3.06	2.22	2.21	1.27	0.17	11.12	12.81
% of LTM	89.51	38.89	86.20	100.00	127.75	95.49	17.89	82.07	80.06
1980	0.03	0.12	2.67	1.43	3.31	0.76	2.41	10.73	12.58
% of LTM	2.10	5.13	75.21	64.41	191.33	57.14	253.68	79.19	78.63
1981	0.66	1.30	3.71	1.57	4.05	2.75	0.23	14.27	15.76
% of LTM	46.15	55.56	104.51	70.72	234.10	206.77	24.21	105.31	98.50
1982	1.85	4.32	3.43	2.02	2.63	1.77	6.51	22.53	26.58
% of LTM	129.37	184.62	96.62	90.99	152.02	133.08	685.26	166.27	166.13
1972-1982	1.77	2.59	3.43	1.57	1.90	1.91	1.51	14.67	17.30
% of LTM	123.78	110.68	96.62	70.72	109.83	143.61	158.95	108.27	108.13

Table 2. Precipitation in inches for growing-season months and the annual total precipitation for 1997-2004, Dickinson, North Dakota.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Growing Season	Annual Total
Long-term mean 1892-2007	1.43	2.34	3.55	2.22	1.73	1.33	0.95	13.55	16.00
1997	3.29	0.92	2.19	6.36	0.91	0.09	0.98	14.74	23.13
% of LTM	230.07	39.32	61.69	286.49	52.60	6.77	103.16	108.78	144.56
1998	0.85	1.86	6.55	1.82	2.90	2.03	4.50	20.51	17.63
% of LTM	59.44	79.49	184.51	81.98	167.63	152.63	473.68	151.37	110.19
1999	1.48	3.94	1.99	0.99	3.23	2.25	0.32	14.20	12.81
% of LTM	103.50	168.38	56.06	44.59	186.71	169.17	33.68	104.80	80.06
2000	1.38	1.80	3.09	3.45	0.35	1.11	0.73	11.91	12.58
% of LTM	96.50	76.92	87.04	155.41	20.23	83.46	76.84	87.90	78.63
2001	2.08	1.75	7.15	3.99	0.00	2.53	0.24	17.74	15.76
% of LTM	145.45	74.79	201.41	179.73	0.00	190.23	25.26	130.92	98.50
2002	1.39	2.06	4.75	2.98	2.81	0.17	1.31	15.47	26.58
% of LTM	97.20	88.03	133.80	134.23	162.43	12.78	137.89	114.17	166.13
2003	0.69	2.67	2.81	0.93	1.46	2.17	0.72	11.45	12.59
% of LTM	48.25	114.10	79.15	41.89	84.39	163.16	75.79	84.50	78.69
2004	0.96	1.40	0.54	2.42	0.63	1.53	2.78	10.26	15.54
% of LTM	67.13	59.83	15.21	109.01	36.42	115.04	292.63	75.72	97.13
1997-2004	1.52	2.05	3.63	2.87	1.54	1.49	1.45	14.54	17.08
% of LTM	106.29	87.61	102.25	129.28	89.02	112.03	152.63	107.31	106.75

Table 3. Evaluation of mean herbage yield on native rangeland pasture fertilization trial, 1972-1988.

Years	Unfertilized Mean Herbage Yield lbs/ac	Fertilized Mean Herbage Yield lbs/ac	Weight Difference from Unfertilized lbs/ac	Percent Difference from Unfertilized %
1972	3160.00	4421.00	1261.00	39.91
1973	2367.00	3448.00	1081.00	45.67
1974	3079.00	5270.00	2191.00	71.16
1975	2462.00	4069.00	1607.00	65.27
1976	2315.00	2842.00	527.00	22.76
1977	1640.00	2021.00	381.00	23.23
1978	1998.95	3201.20	1202.25	60.14
1979	1308.90	1976.55	667.65	51.01
1980	1296.45	1386.85	90.40	6.97
1981	1809.15	2263.05	453.90	25.09
1982	1911.60	3657.95	1746.35	91.36
1983				
1984	1115.00			
1985	1279.30			
1986	1702.01			
1987	1622.56			
1988	451.23			

Table 4. Monthly dry matter weight in pounds per acre for treatments on the evaluation of native rangeland pasture fertilization trial, 1982.

Plant Categories Treatments	15 May	15 Jun	15 Jul	15 Aug	15 Sep
Unfertilized					
cool season	429.6	834.9	1506.1	1232.0	1147.7
warm season	9.3	178.1	520.2	965.9	404.4
total native grass	438.9	1013.0	2026.3	2197.9	1552.1
introduced grass	0.0	0.0	0.0	0.0	0.0
forbs	31.4	199.5	231.6	222.6	203.4
total yield	470.3	1212.5	2257.9	2420.5	1755.5
Fertilized					
cool season	1085.4	2690.6	3260.0	2332.8	2233.6
warm season	54.2	71.0	229.8	162.7	126.1
total native grass	1139.6	2761.6	3489.8	2495.5	2359.7
introduced grass	0.0	201.2	895.9	707.1	264.0
forbs	10.7	205.5	480.3	638.0	133.2
total yield	1150.3	3168.3	4866.0	3840.6	2756.9

Table 5. Percent composition of weight yield for treatments on the evaluation of native rangeland pasture fertilization trial, 1982.

Plant Categories Treatments	15 May	15 Jun	15 Jul	15 Aug	15 Sep
Unfertilized					
cool season	91.35	68.86	66.70	50.90	65.38
warm season	1.98	14.69	23.04	39.90	23.04
total native grass	93.32	83.55	89.74	90.80	88.41
introduced grass	0.0	0.0	0.0	0.0	0.0
forbs	6.68	16.45	10.26	9.20	11.59
total yield	470.3	1212.5	2257.9	2420.5	1755.5
Fertilized					
cool season	94.36	84.92	67.00	60.74	81.02
warm season	4.71	2.24	4.72	4.24	4.57
total native grass	99.07	87.16	71.72	64.98	85.59
introduced grass	0.0	6.35	18.41	18.41	9.58
forbs	0.93	6.49	9.87	16.61	4.83
total yield	1150.3	3168.3	4866.0	3840.6	2756.9

Table 6. Dry matter weight in pounds per acre for treatments on the evaluation of native rangeland pasture fertilization trial, 1982-1988.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Yield
1982							
unfertilized	517.15	898.28	281.90	1697.33	0.0	214.27	1911.60
fertilized	147.40	2392.55	236.70	2776.65	517.05	364.25	3657.95
1983							
unfertilized							
fertilized							
1984							
unfertilized	222.39	324.14	448.77	995.30	0.0	119.70	1115.00
fertilized							
1985							
unfertilized	231.72	364.06	615.47	1211.25	0.0	68.05	1279.30
fertilized							
1986							
unfertilized	379.73	519.63	587.30	1486.66	0.0	215.35	1702.01
fertilized							
1987							
unfertilized	339.96	457.55	676.40	1473.91	0.0	148.65	1622.56
fertilized							
1988							
unfertilized	92.03	89.54	208.58	390.15	0.0	61.08	451.23
fertilized							

Table 7. Percent composition of weight yield for treatments on the evaluation of native rangeland pasture fertilization trial, 1982-1988.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Yield
1982							
unfertilized	27.05	46.99	14.75	88.79	0.0	11.21	1911.60
fertilized	4.03	65.41	6.47	75.91	14.13	9.96	3657.95
1983							
unfertilized							
fertilized							
1984							
unfertilized	19.95	29.07	40.25	89.26	0.0	10.74	1115.00
fertilized							
1985							
unfertilized	18.11	28.46	48.11	94.68	0.0	5.32	1279.30
fertilized							
1986							
unfertilized	22.31	30.53	34.51	87.35	0.0	12.65	1702.01
fertilized							
1987							
unfertilized	20.95	28.20	41.69	90.84	0.0	9.16	1622.56
fertilized							
1988							
unfertilized	20.40	19.84	46.22	86.46	0.0	13.54	451.23
fertilized							

Table 8. Basal cover of plant categories for treatments on the evaluation of native rangeland pasture fertilization trial, 1982-1988.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Basal Cover
1982							
unfertilized	9.94	4.47	6.64	21.05	0.36	1.40	22.81
fertilized	3.20	6.27	5.70	15.17	1.96	0.34	17.47
1983							
unfertilized							
fertilized							
1984							
unfertilized							
fertilized							
1985							
unfertilized	14.78	4.48	8.93	28.19	0.08	2.48	30.75
fertilized							
1986							
unfertilized	10.11	8.69	12.18	30.98	0.0	4.66	35.64
fertilized							
1987							
unfertilized	4.96	5.42	10.30	20.68	0.0	4.69	25.37
fertilized							
1988							
unfertilized	8.51	5.21	7.88	21.60	0.0	5.23	26.83
fertilized							

Table 9. Evaluation of mean herbage yield on native rangeland pasture fertilization trial, 1997-2004.

Years	Unfertilized Mean Herbage Yield lbs/ac	Fertilized Mean Herbage Yield lbs/ac	Weight Difference from Unfertilized lbs/ac	Percent Difference from Unfertilized %
1997	1442.66a	2238.32b	795.66	55.15
1998	1385.57a	1997.12a	611.55	44.14
1999	1157.94a	2293.04b	1135.10	98.03
2000	696.71a	1132.48b	435.77	62.55
2001	1495.00a	3034.71b	1539.71	102.99
2002	1261.17a	1877.24b	616.07	48.85
2003				
2004	705.75a	1090.86b	385.11	54.57

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

Table 10. Dry matter weight in pounds per acre for treatments on the evaluation of native rangeland pasture fertilization trial, 1997-2004.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Yield
1997							
unfertilized	226.21a	279.02a	456.70a	961.94a	159.13a	321.59a	1442.66a
fertilized	238.10a	285.44a	428.87a	952.42a	1063.03b	222.88a	2238.32b
1998							
unfertilized	322.07a	527.35a	305.42a	1154.84a	0.0a	230.73a	1385.57a
fertilized	33.06b	157.47a	204.09a	394.62b	1524.01b	78.50a	1997.12a
1999							
unfertilized	190.30a	501.66a	159.37a	851.33a	168.65a	137.96a	1157.94a
fertilized	27.12b	58.76b	91.82a	177.69b	2031.62b	83.73a	2293.04b
2000							
unfertilized	148.67a	186.49a	165.08a	500.23a	105.37a	91.10a	696.71a
fertilized	40.91a	39.01b	77.78a	157.71b	949.32b	25.45b	1132.48b
2001							
unfertilized	227.64a	465.27a	341.58a	1034.49a	185.06a	275.45a	1495.00a
fertilized	28.31b	44.72b	137.73a	210.75b	2757.11b	66.84b	3034.71b
2002							
unfertilized	217.65a	493.10a	335.87a	1046.61a	31.87a	182.68a	1261.17a
fertilized	29.97b	82.30b	136.54b	248.81b	1551.84b	76.59a	1877.24b
2003							
unfertilized							
fertilized							
2004							
unfertilized	73.50a	286.39a	182.45a	542.34a	51.85a	111.56a	705.75a
fertilized	16.17a	63.99b	135.35a	215.51b	818.50b	56.85a	1090.86b

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

Table 11. Percent composition of weight yield for treatments on the evaluation of native rangeland pasture fertilization trial, 1997-2004.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Yield
1997							
unfertilized	16.01a	19.20a	30.68a	65.90a	12.08a	22.03a	1442.66
fertilized	11.18a	13.23a	20.36a	44.77a	44.73a	10.49b	2238.32
1998							
unfertilized	26.84a	37.44a	21.65a	85.92a	0.0a	14.08a	1385.57
fertilized	1.63b	8.20b	10.25b	20.08b	75.97b	3.95b	1997.12
1999							
unfertilized	18.13a	44.46a	12.83a	75.41a	12.32a	12.26a	1157.94
fertilized	1.44b	2.94b	4.02a	8.40b	88.02b	3.58b	2293.04
2000							
unfertilized	22.35a	26.72a	23.09a	72.17a	13.73a	14.10a	696.71
fertilized	4.01b	3.80b	6.65b	14.46b	83.27b	2.27b	1132.48
2001							
unfertilized	16.25a	32.83a	21.88a	70.97a	10.99a	18.04a	1495.00
fertilized	1.12b	1.83b	4.77b	7.72b	89.17b	2.40b	3034.71
2002							
unfertilized	17.57a	39.79a	26.47a	83.83a	2.26a	13.91a	1261.17
fertilized	1.56b	4.40b	7.23b	13.18b	82.73b	4.09b	1877.24
2003							
unfertilized							
fertilized							
2004							
unfertilized	10.42a	40.59a	26.01a	77.02a	7.31a	15.66a	705.75
fertilized	1.61b	5.88b	12.81a	20.29b	74.47b	5.23b	1090.86

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

Table 12. Basal cover of plant categories for treatments on the evaluation of native rangeland pasture fertilization trial, 1997-2004.

Years Treatments	Warm Season Grass	Cool Season Grass	Sedge	Total Native Grass	Domesticated Grass	Forbs	Total Basal Cover
1997							
unfertilized							
fertilized							
1998							
unfertilized	9.93a	3.63a	4.33a	17.93a	1.17a	1.97a	21.07a
fertilized	2.70b	0.85b	3.37a	6.92b	4.67b	0.73a	12.32b
1999							
unfertilized	7.90a	7.16a	5.33a	20.39a	4.09a	2.57a	27.05a
fertilized	2.43b	1.72b	2.02b	6.17b	17.40b	0.71b	24.28a
2000							
unfertilized	7.25a	3.79a	6.17a	17.21a	1.49a	2.61a	21.31a
fertilized	3.25a	0.92b	5.47a	9.64b	10.40b	0.63b	20.67a
2001							
unfertilized	6.87a	6.20a	8.17a	21.24a	2.86a	4.37a	28.47a
fertilized	2.35b	1.73b	5.63a	9.71b	17.90b	0.82a	28.43a
2002							
unfertilized	7.00a	5.81a	9.77a	22.58a	2.87a	5.10a	30.55a
fertilized	2.48b	1.20b	4.52b	8.20b	13.09b	1.65b	22.94b
2003							
unfertilized	7.92a	4.28a	8.28a	20.48a	1.27a	2.98a	24.73a
fertilized	2.85b	1.20b	6.72a	10.77b	8.88b	2.17a	21.82a
2004							
unfertilized	4.48a	4.34a	6.10a	14.92a	6.25a	5.25a	26.42a
fertilized	1.37a	1.45b	6.20a	9.02b	16.64b	1.87b	27.53a

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

Table 13. Basal cover of plant subcategories for treatments on the evaluation of native rangeland pasture fertilization trial, 1982, 1985-1988, 1998-2004.

Years Treatments	Warm Season Grass		Cool Season Grass		Domesticated Grass		
	mid warm	short warm	mid cool	short cool	crested wheatgrass	smooth bromegrass	bluegrass
1982							
unfertilized	0.64	9.30	2.47	2.00	0.00	0.03	0.33
fertilized	0.03	3.17	4.80	1.47	0.67	0.63	0.66
1985-1988							
unfertilized	1.56	8.39	2.83	3.36	0.00	0.03	0.00
fertilized							
1998-2004							
unfertilized	0.95	6.98	3.04	2.37	0.21	1.65	0.59
fertilized	0.19	2.55	1.03	0.31	4.54	4.21	3.64

Table 14. Fate of applied fertilizer nitrogen on native rangeland pasture, 1972-1982, following first approximation percentages of fertilizer nitrogen fate in grazed semiarid rangeland developed by Power (1977).

Biotic and Abiotic Nitrogen Sinks	Fate of N as Percent of Applied Data from Power 1977 %	Fate of N from 50 lbs N/ac per year lbs N/yr	Fate of N from 550 lbs N/ac per 11 years lbs N/11 yrs
Retained in Ecosystem	92%	46.0	506.0
Plants	22%	11.0	121.0
aboveground herbage	2%	1.0	11.0
crown	1%	0.5	5.5
roots	19%	9.5	104.5
Litter	16%	8.0	88.0
Soil Mineral Nitrogen	41%	20.5	225.5
ammonium NH_4	2%	1.0	11.0
nitrate NO_3	39%	19.5	214.5
Soil Organic Nitrogen unmeasured estimate	13%	6.5	71.5
Lost to Ecosystem	8%	4.0	44.0
Beef Tissue	3%	1.5	16.5
Gaseous Losses unmeasured estimate	5%	2.5	27.5
Leaching	0%	0.0	0.0

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Influence of Soil Mineral Nitrogen on Native Rangeland Plant Water Use Efficiency and Herbage Production

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Native rangelands managed by traditional grazing practices are deficient in available soil mineral nitrogen and produce less than potential quantities of herbage biomass (Wight and Black 1972). The biogeochemical processes of these rangeland ecosystems typically function at levels that cycle nitrogen at rates of about 59 pounds or less of mineral nitrogen per acre per year and produce only one half to one third of the potential quantities of herbage biomass (Wight and Black 1972). The remedy for the problem of low herbage production on native rangeland is not repetitive applications of nitrogen fertilizer because the additional herbage produced from nitrogen fertilization has unprofitably high costs (Manske 2009b) and the long-term effects from nitrogen fertilization cause shifts in plant species composition with reductions of the native grass species and increases of the domesticated and introduced grass species (Manske 2009a). However, the results from more than three decades of nitrogen fertilization research on native rangelands provides insight into the underlying causes of the problem of herbage production at below potential quantities on native rangelands managed by traditional grazing practices.

Nitrogen fertilization of native rangeland increases the quantity of available soil mineral nitrogen. Total herbage biomass production on native rangeland increases with the increases in quantity of soil mineral nitrogen (Rogler and Lorenz 1957, Whitman 1957, Whitman 1963, Smika et al. 1965, Goetz 1969, Power and Alessi 1971, Lorenz and Rogler 1972, Goetz 1975, Taylor 1976, Whitman 1976, Goetz et al. 1978, Wight and Black 1979). The greater quantities of available soil mineral nitrogen cause the soil water use efficiency to improve in grassland plants (Smika et al. 1965, Wight and Black 1972, Whitman 1976, 1978). Water use efficiency (pounds of herbage produced per inch of water use) is difficult to measure quantitatively because soil water can be lost through evaporation or transpiration. Precipitation use efficiency (pounds of herbage produced per inch of precipitation received) is less complicated to measure than water use efficiency. Wight and Black (1972) found that precipitation use efficiency of grasslands improved with increased quantities of soil mineral nitrogen and that the pounds of herbage produced per inch of precipitation were greater on the nitrogen fertilized treatments than on the unfertilized treatments. Wight and Black (1979) compared herbage production on traditionally managed rangeland with the typical ambient deficiency of available mineral nitrogen to herbage production on nitrogen fertilized rangeland without a deficiency of available mineral nitrogen. During ten years of study with normal growing season precipitation, the deficiency of mineral nitrogen on the traditionally managed rangeland caused the weight of herbage production per inch of precipitation received to be reduced an average of 49.6% below the herbage produced per inch of precipitation on the rangeland without a mineral nitrogen deficiency.

Nitrogen cycling in Northern Plains rangeland ecosystems managed by traditional grazing practices is inadequate to supply the quantity of mineral nitrogen necessary for minimum potential herbage production. A deficiency in available mineral nitrogen causes reductions in grassland plant water use efficiency and reductions in herbage biomass production to below potential levels during growing seasons with normal precipitation and no deficiency in available water. During growing seasons with below normal precipitation, both the deficiency in available water and the deficiency in available mineral nitrogen contribute to the resulting reductions in herbage production. During drought growing seasons, the percent reduction in herbage production is greater than the percent reduction in precipitation because of the additional reductions in water use efficiency and herbage production caused by the deficiency of mineral nitrogen. Semiarid rangelands would produce herbage biomass at the maximum level for whatever soil water was available if the ecosystems were not deficient in mineral nitrogen (Power and Alessi 1971). Herbage production on native rangeland ecosystems at minimum potential herbage yields would require nitrogen cycling at a rate of about 100 pounds of available mineral nitrogen per acre per year and that maximum potential herbage yields would be produced at rates of about 165 pounds of mineral nitrogen per acre per year (Wight and Black 1972).

Native rangeland plants need hydrogen, carbon, and nitrogen to produce herbage biomass. The hydrogen comes from soil water absorbed through the roots. The carbon comes from atmospheric carbon dioxide fixed through photosynthesis in the leaves. The nitrogen comes from the mineral nitrogen mineralized from soil organic nitrogen by rhizosphere microorganisms (Manske 2007). The total amount of energy fixed by chlorophyllous plants on rangeland ecosystems is not limited by the availability of radiant energy from the sun or by the availability of atmospheric carbon dioxide. The availability of water, which is an essential requirement for plant growth and has a dominant role in physiological processes, does not limit herbage production on rangeland ecosystems to the extent that mineral nitrogen availability does (Wight and Black 1972). Available soil mineral nitrogen is the major herbage growth limiting factor in Northern Plains rangelands (Wight and Black 1979). Grassland soils are not deficient of nitrogen and do not require application of additional fertilizer nitrogen. Most of the grassland nitrogen is immobilized in the soil as organic nitrogen in living tissue and nonliving detritus. Grassland soils in the Northern Plains contain about 3 to 8 tons of organic nitrogen per acre. Soil organic nitrogen must be converted into mineral nitrogen through mineralization by soil microorganisms in order to be available to grassland plants. The greater the biomass of soil microorganisms, the greater the quantity of available mineral nitrogen.

Rangelands managed by the twice-over rotation grazing strategy are not deficient in available mineral nitrogen. The biologically effective twice-over rotation grazing management strategy is designed to use partial defoliation of grass tillers at beneficial phenological growth stages to meet the biological requirements of grassland plants and to stimulate rhizosphere organism activity that enhances the biogeochemical processes in grassland ecosystems and increases the quantity of organic nitrogen mineralized into inorganic (mineral) nitrogen at amounts sufficient for herbage production at maximum potential yield levels (Manske 2007).

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Enhancement of the Nitrogen Cycle Improves Native Rangeland

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Available soil mineral nitrogen is the major limiting factor of herbage growth on native rangelands (Wight and Black 1979). Rangeland soils, however, are not deficient of nitrogen. Most of the nitrogen in rangeland ecosystems is in the organic form. A large amount of the organic nitrogen is immobilized in living tissue of microorganisms, plants, and animals as essential constituents of proteins and nucleic acids. An additional large amount of the soil organic nitrogen is contained in the soil organic matter detritus that is at various stages of physical breakdown and decomposition and is derived from dead organisms, excreta, and sloughed material. A small portion of the soil nitrogen is in the mineral form as ammonium, nitrate, and nitrite. The amount of available mineral nitrogen in the soil is affected by the rate of mineralization of the organic nitrogen by soil microorganisms. A minimum rate of mineralization of about 100 pounds of mineral nitrogen per acre per year is required to sustain herbage production at potential levels on native rangeland (Wight and Black 1972). Mineralization at these high rates can not be obtained from traditional grazing practices (Wight and Black 1972). Grazing management specifically designed to enhance soil microorganism activity can be implemented to obtain mineralization rates of 100 pounds of mineral nitrogen per acre per year or greater. Enhancement of the nitrogen cycle, with increases in the quantity of available soil mineral nitrogen, increases herbage growth and production and improves new wealth generation from native rangeland natural resources.

The nitrogen cycle in rangeland ecosystems is complex. Nitrogen is versatile and has several oxidation states and can exist as a gas, a dissolved cation or anion, a precipitated salt, an adsorbed or interlayer ion in clay, and as dissolved or solid organic molecules of varying complexity (Russelle 1992). Nitrogen moves through a variety of biological and chemical pathways and the movement within the cycle is difficult to predict and highly variable among different climatic zones because the nitrogen cycle pathways are directly or indirectly influenced by regional temperature and moisture regimes. Biological pathways are also influenced by metabolic rates of microorganisms, plants, and animals (Russelle 1992). The nitrogen cycle in rangelands is open and has inputs (gains) that transfer in from outside sources and has outputs (losses) that transfer out of the ecosystem.

Nitrogen inputs on rangelands arrive through atmospheric pathways as wet deposits in rain, snow, or hail and as dry deposits of gases or minute particles. 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 on rangeland in precipitation. Inorganic nitrogen, as ammonium (NH_4) and nitrate (NO_3), and complex organic compounds removed by erosive forces from distant soil surfaces are deposited on rangelands in precipitation, wind, and sometimes overland water movement. The ambient amount of wet and dry nitrogen deposition in temperate regions from natural sources is around 5 to 6 pounds per acre per year (Brady 1974). Nitrogen deposits from other sources are primarily nitrogen oxides expelled in the exhaust emissions from cars, aircraft, and factories. The amount of nitrogen deposits from sources related to anthropogenic activity is highly variable, influenced by distance and direction from population centers, and can range from 0 to 15 pounds per acre per year or greater (Gibson 2009).

Symbiotic and nonsymbiotic fixation of atmospheric nitrogen is an input source of nitrogen for some mesic grasslands but generally not for semiarid rangelands. Strains of symbiotic Rhizobium bacteria form nodules on the roots of legumes and can fix atmospheric dinitrogen gas (N_2) in soil air and synthesize it into complex forms. Some of this fixed nitrogen is required by the bacteria, some of the nitrogen can be available to the host plant, and some of the nitrogen can be passed into the surrounding soil by excretion or by the sloughing off of the roots with nodules (Brady 1974). Legumes are not an abundant component in native rangelands and the legumes that are present in mature soils have low levels of nodulation and may not fix nitrogen (Gibson 2009). A few nonsymbiotic soil microorganisms are able to fix atmospheric dinitrogen (N_2) from soil air into their body tissue (Brady 1974). Nitrogen fixation by free living soil bacteria in semiarid rangelands is not known to be important and considered to be insignificantly low or nonexistent (Legg 1995, Gibson 2009).

Potential outputs for nitrogen from rangeland ecosystems can be lost to the atmosphere through denitrification of mineral nitrogen, ammonia volatilization, and volatilization by fire; lost through transfers by wind and water erosion of surface soil and by hydrologic leaching; and lost through animal production of both domesticated livestock and wildlife.

Denitrification is the reduction of inorganic nitrogen by removal of oxygen from the nitrite (NO_2) and nitrate (NO_3) mineral nitrogen to form gaseous nitrous oxides (NO and N_2O) or nonreactive dinitrogen gas (N_2) and can be mediated both chemically and biologically (Brady 1974). Losses from denitrification in rangelands is greatest in the nitrous oxide form (N_2O), followed by losses in the dinitrogen form (N_2). Losses in the nitric oxide form (NO) occur on rangelands only under acid conditions (Brady 1974). Chemical denitrification is of little importance in native rangelands unless nitrate is present in high concentrations (Russelle 1992). Biological denitrification occurs when soil microorganisms are deficient of oxygen as a result of poor drainage or poor soil structure causing soil saturation or lack of aeration. Denitrification probably accounts for only a small part of the total nitrogen losses from pastures and rangelands (Legg 1975, Gibson 2009).

Ammonia volatilization can occur near the soil surface during mineralization of soil organic nitrogen by soil microorganisms (Foth 1978). Gaseous ammonia (NH_3) forms as an intermediate stage and is usually readily hydrolyzed to form ammonium (NH_4) which is a stable form of mineral nitrogen. However, under conditions of increasing aridity and decreasing availability of hydrogen ions, the hydrolyzation process decreases and the amount of ammonia that escapes into the atmosphere by volatilization increases (Gibson 2009).

Nitrogen contained in aboveground herbage and litter is volatilized when rangelands are burned by prescribed fire and wild fire. Combustion causes nitrogen losses approaching 90%, primarily as ammonia (NH_3), dinitrogen oxide (N_2O), and other nitrogen oxides (Russelle 1992). Little belowground nitrogen is volatilized when the soil is moist during a burn, however, when the soil is dry, belowground temperatures can increase enough to denature protein, killing portions of the grass crowns and root material and volatilizing some belowground nitrogen.

Nitrogen in soil, litter, and organic detritus can be transferred from one area to another through movement by wind and water. The transferred nitrogen is a loss from one area and a gain at the deposition area. Nitrogen losses through erosion removal are variable and influenced by live plant density, litter cover, extent of branching fiberous root systems, and soil infiltration rates. The quantity of nitrogen lost through erosional movement can be decreased with enhancement of the nitrogen cycle and improvement in productivity of the rangeland ecosystem (Russelle 1992).

Soluble nitrate (NO_3) moves downward in the soil profile with soil water. In mesic grasslands, nitrogen can be lost as a result of water movement below the rooting depth (Russelle 1992). None of the mineral nitrogen in western rangelands is lost by hydrologic leaching through the soil profile (Power 1970) because very little water moves below the three foot soil depth and water loss by leaching is low or nonexistent in arid and semiarid rangelands under cover of perennial vegetation (Brady 1974, Wight and Black 1979).

Livestock grazing semiarid rangelands in the Northern Plains consume about 25% of the aboveground herbage, leaving a significant part of the nitrogen absorbed by the growing vegetation in the remaining live aboveground herbage, the standing dead vegetation, and the litter. Most of the nitrogen consumed by grazing livestock and wildlife is returned to the soil surface in urine and feces waste. Almost all of the nitrogen in urine is immediately available to plants. A portion of the urea in urine can be volatilized in warm dry conditions (Gibson 2009). Grazing animals retain only a small amount of the nitrogen consumed, about 15% to 17% in a nonlactating animal and about 30% in a lactating animal (Russelle 1992). The quantity of nitrogen lost as animal product increases as enhancement of the nitrogen cycle improves productivity of the rangeland ecosystem.

Differences in nitrogen inputs and outputs on rangeland soils determine the quantity of net accumulation of nitrogen. The total nitrogen content in soils accumulates gradually over several thousand years. Organic matter accumulation is benefitted in northern soils because little or no chemical oxidation activity of organic matter takes place during the cold periods. The dark surface layer of most soils in the Northern Plains has an accumulation of 2% to 5% organic matter (Larson et al. 1968, Wright et al. 1982). An acre of soil 6 inches deep contains about 1000 pounds of nitrogen for each percent of organic matter (Foth 1978). Nitrogen content and percent organic matter decrease with soil depth. A net accumulation of 2 pounds of nitrogen per acre per year results in a soil with 5 tons of nitrogen per acre in 5000 years.

The nitrogen cycle within rangeland soils functions around the two processes of immobilization and mineralization. These processes take place simultaneously with plant growth, dieback, and decomposition (Legg 1975). Immobilization is the process of tying up nitrogen in organic forms.

Mineralization is the process of converting organic nitrogen into mineral (inorganic) nitrogen.

Biological immobilization of nitrogen occurs when autotrophic plants and soil microorganisms absorb inorganic nitrogen and build essential organic nitrogen compounds of amino acids and nucleic acids. Amino acids are building blocks of proteins that form enzymes, hormones, and important structural components of cells. Nucleic acids, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), are the genetic material that control all cellular functions and heredity. In rangeland soils, nitrogen is tied up in organic forms for three to four years (Power 1972). Biological immobilization of mineral nitrogen by plants and soil microorganisms is beneficial for rangeland ecosystems because about 95% of the total nitrogen is preserved within the soil as organic nitrogen and not subjected to great potential losses through denitrification and ammonia volatilization (Legg 1975, Gibson 2009).

Chemical immobilization of mineral nitrogen by adsorption of ammonium onto clay particles can be an advantage or a disadvantage for rangeland ecosystems depending on the type and amount of clay present. The ammonium ions are apparently the right size to fit into the cavities between crystal units normally occupied by potassium making the ammonium more or less a rigid part of the crystal (Brady 1974, Foth 1978). The type of clay mineral affects the retention of the ammonium. Clay materials with expanding lattices, such as vermiculite, illite, and montmorillonite, have greater surface area and adsorptive capacity for ammonium than clay minerals with nonexpanding lattices, such as kaolinite (Brady 1974, Legg 1975). Chemical immobilization of ammonium to clay material protects that portion of the soil mineral nitrogen from potential losses. The ammonium is slowly released from the clay and made available to plants and soil microorganisms. When the quantity of clay is too high or when the ammonium release rate is too slow, available mineral nitrogen may be too low to maintain ecosystem productivity at potential levels.

Mineralization occurs when organic nitrogen immobilized in living tissue or contained in soil organic matter detritus is processed by soil microorganisms to form mineral nitrogen. Mineralization consists of a series of reactions. 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 released ammonia is readily hydrolyzed into ammonium (NH_4) which becomes part of the inorganic nitrogen pool in the soil.

Some of the ammonium produced during the mineralization process by soil microorganisms or the ammonium released from adsorption to clay material is nitrified in a complex two stage process coordinated by two distinct groups of soil bacteria. Ammonium is nitrified by enzyme oxidation that releases energy for the first group of bacteria and produces nitrite (NO_2) and water. In short order, the second group of bacteria oxidize the nitrite by enzyme activity that releases energy and produces nitrate (NO_3) which becomes part of the inorganic nitrogen pool in the soil. The speed of this coordinated two stage nitrification process prevents accumulation of nitrite in the soil. Concentrations of nitrite are toxic to higher plants (Brady 1974).

The quantity of available soil mineral nitrogen varies cyclically 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 a dynamic cycle 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. This cycle in available soil mineral nitrogen results in three peaks and three low periods during the growing season (Whitman 1975). The quantity of mineral nitrogen increases an average of 25% to 50% between the low periods and the peaks in the cycle with some variations occurring on different range sites and at different soil depths (Goetz 1975).

Mineralization and nitrification processes of soil microorganism activity start slowly in the spring when the soil temperature permits formation of liquid water around 30° F. Available mineral nitrogen increases with increases in soil temperature and microorganism biomass reaching the first peak in mineral nitrogen around mid May just prior to start of rapid plant growth. The quantity of mineral nitrogen decreases rapidly with increasing plant growth rates during spring reaching the first low period during June and the first two weeks of July. The second peak in mineral nitrogen is reached at the end of the active growing season usually around late July or early August. A second low period in mineral nitrogen occurs from around mid August to mid or late September when plants have slow growth rates and during growth and development of fall tillers and fall tiller buds that will produce the early plant growth during the subsequent growing season. The third peak in mineral nitrogen occurs around mid October just prior to the end of the perennial plant growing season during autumn. Mineral nitrogen declines during the third low period as winter freeze up approaches (Goetz 1975, Whitman 1975).

The greater the quantity of mineral nitrogen available during periods of active plant growth, the greater the quantity of herbage biomass production. Rangeland ecosystem biogeochemical processes that cycle nitrogen need to function at rates that provide 100 pounds of mineral nitrogen per acre to produce the minimum potential quantity of herbage biomass and need to provide 165 pounds of mineral nitrogen per acre to produce the maximum potential quantity of herbage biomass (Wight and Black 1972) (table 1).

Traditional management practices, like 6.0 month seasonlong, repeated seasonal, and deferred grazing, were designed to use rangelands as a source of grazable forage for livestock and, even when operated with strong land stewardship ethics, traditional practices do not provide mineral nitrogen at quantities great enough to produce the potential quantity of herbage. Rangelands managed for about 35 years with a moderately stocked 6.0 month seasonlong grazing practice provided 62 pounds of mineral nitrogen per acre (Manske 2009), rangelands managed with an unspecified traditional grazing practice provided 59 pounds of mineral nitrogen per acre (Wight and Black 1972), and rangelands managed for 35 years with a low to moderately stocked 4.5 to 5.0 month deferred grazing practice provided 31 pounds of mineral nitrogen per acre (Manske 2008) (table 1). Rangelands managed with traditional grazing practices provide mineral nitrogen at deficiency rates of less than 100 pounds per acre causing decreases in plant water use efficiency and reducing herbage biomass production an average of 49.6% per inch of precipitation (Wight and Black 1979) (table 1). As a consequence of traditional grazing practices providing low quantities of mineral nitrogen and producing less than potential quantities of herbage biomass, native rangelands are incorrectly considered to be low producing, low income generating, resources.

Grazing management that is designed to meet the biological requirements of the plants and soil microorganisms and to stimulate ecosystem biogeochemical processes provide greater quantities of mineral nitrogen than do traditional practices. During the seventh grazing season, rangelands managed with a three pasture twice-over rotation grazing system provided 178 pounds of mineral nitrogen per acre (Manske 2008) (table 1). The greater quantity of mineral nitrogen resulted from greater soil microorganism activity. The twice-over rotation grazing system stimulated soil microorganism activity in the rhizosphere by increasing the quantity of plant fixed carbon exudated through grass roots into the rhizosphere. Removal of 25% to 33% of the leaf material by grazing livestock after the three and a half new leaf stage and before the flowering (anthesis) stage increased plant carbon exudates (Manske 2007). Soil microorganism growth and activity is limited by available carbon. Rhizosphere organisms increase in biomass and activity with increases in carbon. The rhizosphere volume on traditional grazing practices after twenty years of 6.0 month seasonlong and 4.5 month seasonlong was 50 and 68 cubic feet per acre, respectively (table 1). The rhizosphere volume was 227 cubic feet per acre on a twice-over rotation grazing system after twenty years (Manske 2008) (table 1). The greater rhizosphere organism biomass on rangelands managed with a twice-over rotation system had increased activity that mineralized and nitrified a greater quantity of organic nitrogen into mineral nitrogen. The greater quantity of available soil mineral nitrogen permitted the production of maximum potential herbage biomass, the growth of greater pounds of calf weight per acre, the generation of greater wealth per acre, and the improvement of native rangeland natural resources (Manske et al. 2008).

Table 1. Grazing management effects on mineral nitrogen and rhizosphere volume in native rangelands.

Standards for Mineral Nitrogen		Mineral Nitrogen	Source
Minimum potential herbage biomass		100 lbs/ac	Wight and Black 1972
Maximum potential herbage biomass		165 lbs/ac	Wight and Black 1972
Mineral nitrogen deficiency of less than 100 lbs/ac results in 49.6% reduction in herbage production per inch of precipitation.			Wight and Black 1979
Grazing Management		**Mineral Nitrogen**	
4.5-5.0 month Deferred	35 yrs	31 lbs/ac	Manske 2008
Traditional, not specified	long-term	59 lbs/ac	Wight and Black 1972
6.0 month Seasonlong	35 yrs	62 lbs/ac	Manske 2009
4.5 month Seasonlong	6 yrs	112 lbs/ac	Manske 2008
Twice-over Rotation	6 yrs	178 lbs/ac	Manske 2008
Grazing Management		**Rhizosphere Volume**	
6.0 month Seasonlong	20 yrs	50 ft^3/ac	Manske 2008
4.5 month Seasonlong	20 yrs	68 ft^3/ac	Manske 2008
Twice-over Rotation	20 yrs	227 ft^3/ac	Manske 2008

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