Long-term agroecosystem research on northern Great Plains mixed-grass prairie near Mandan, North Dakota

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[1]USDA – Agricultural Research Service, Northern Great Plains Research Laboratory, Mandan, ND 58554 USA (e-mail: matt.sanderson@ars.usda.gov); and [2]USDA – Agricultural Research Service, Rangeland Resources Research Unit, Cheyenne, WY 82009 USA.

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Sanderson, M. A., Liebig, M. A., Hendrickson, J. R., Kronberg, S. L., Toledo, D., Derner, J. D. and Reeves, J. L. 2015. **Long-term agroecosystem research on northern Great Plains mixed-grass prairie near Mandan, North Dakota**. Can. J. Plant Sci. **95**: 1101–1116. In 1915, a stocking rate experiment was started on 101 ha of native mixed-grass prairie at the Northern Great Plains Research Laboratory (NGPRL) near Mandan, ND (100.9132N, 46.7710W). Here, we document the origin, evolution, and scientific outcomes from this long-term experiment. Four pastures of 12.1, 20.2, 28.3, and 40.5 ha were laid out and stocked continuously from May until October with 2-yr-old or yearling beef steers at four rates [initially 0.98, 1.39, 1.83, and 2.4 animal unit months ha^{-1}]. The experiment generated some of the first information on the resilience of mixed-grass prairie to grazing and drought and relationships of livestock productivity to soil moisture for predictive purposes. After 1945, the experiment was reduced to the light and heavy stocking rate pastures only, which have been managed and grazed in approximately the same manner to the present day. The pastures were used to assess responses of vegetation to fertilizer in the 1950s and 1960s, develop grazing readiness tools in the 1990s, and assess remote sensing technologies in the 2000s. The long-term pastures currently serve as a unique resource to address contemporary questions dealing with drought, soil quality, carbon dynamics, greenhouse gas emissions, invasive species, and climate change.

Key words: Climate variability, grazing management, semiarid rangeland, Long-term Agro-Ecosystem Research (LTAR) Network, National Ecological Observatory Network (NEON), northern mixed-grass prairie

Sanderson, M. A., Liebig, M. A., Hendrickson, J. R., Kronberg, S. L., Toledo, D., Derner, J. D. et Reeves, J. L. 2015. **Recherche de longue haleine sur les écosystèmes agricoles des prairies à graminées mixtes dans le nord des Grandes Plaines près de Mandan, au Dakota Nord**. Can. J. Plant Sci. **95**: 1101–1116. En 1915 débutait une expérience sur la charge de bétail, au laboratoire de recherche du nord des Grandes Plaines, près de Mandan, dans le Dakota Nord (100,9132 N 46,7710 O). L'expérience s'est déroulée sur 101 ha de prairie naturelle à mélange de graminées. Les auteurs exposent l'origine, l'évolution et les résultats scientifiques de cette expérience de longue haleine. Quatre pâturages de 12,1, 20,2, 28,3 et 40,5 ha ont été aménagés, puis des bouvillons de boucherie d'un ou de deux ans y ont été mis à paître de façon ininterrompue de mai à octobre, à quatre taux de chargement (0,98, 1,39, 1,83 et 2,4 unités animales-mois par hectare au départ). L'expérience a produit quelques-unes des premières données sur la résilience des prairies à graminées mixtes à la paissance et à la sécheresse, faisant ressortir les liens entre la productivité du bétail et la teneur en eau du sol, en vue de la formulation de prévisions. À partir de 1945, l'expérience s'est réduite aux capacités de charge la plus faible et la plus élevée, les pâturages étant gérés et exploités à peu près de la même manière qu'ils le sont encore aujourd'hui. Dans les années 1950 et 1960, on a recouru à ces pâturages pour évaluer la réaction de la végétation aux engrais; dans les années 1990, on s'en est servi pour mettre au point des outils de préparation à la paissance et, dans les années 2000, pour évaluer des technologies de télédétection. Ces pâturages à long terme constituent une ressource unique pour l'étude des enjeux contemporains liés à la sécheresse, à la qualité du sol, à la dynamique du carbone, aux émissions de gaz à effet de serre, aux espèces envahissantes et au changement climatique.

Mots clés: Variabilité du climat, gestion de la paissance, grands parcours semi-arides, Long-term Agro-Ecosystem Research (LTAR) Network, National Ecological Observatory Network (NEON), prairie boréale à mélange de graminées

Abbreviations: **AUM**, animal unit month; **NGPRL**, Northern Great Plains Research Laboratory

Long-term research is critical to understanding productivity, vegetation change, and resilience of native grasslands. The need for long-term data is especially acute with climate change and associated extreme weather events. Long-term studies in other agricultural disciplines, such as the Morrow crop rotation plots in Illinois (Odell 1982), the Rothamsted grassland and cropping plots in England (Jenkinson 1991), the Magruder continuous wheat plots at Oklahoma State University (Davis et al. 2003), and several long-term cropping studies in Canada (Lafond and Harker 2012), have generated invaluable insights into the sustainability of agricultural systems.

In the United States, long-term experiment stations [e.g., the Santa Rita Experimental Range (Arizona) established in 1903, the Great Basin Experimental Range (Idaho) and the Jornada Experimental Range (New Mexico) in 1912, and the Central Plains Experimental Range (Colorado) in 1937] have provided institutional commitments to parallel efforts associated with livestock grazing. There are several examples of long-term (>40 yr) rangeland studies in western North America that have provided valuable data on forage productivity (Milchunas et al. 1994), livestock gains (Hart and Ashby 1998), vegetation dynamics (Fuhlendorf and Smeins 1997), the influence of management practices and climatic variability (Fuhlendorf et al. 2001; Molinar et al. 2011; Douwes and Willms 2012), fuel loads in shrublands (Davies et al. 2010), soils (Dormaar and Willms 1998; Evans et al. 2012; Li et al. 2012), and animal and plant diversity (Milchunas et al. 1998; Hart 2001).

The Northern Great Plains Research Laboratory (NGPRL) at Mandan, ND, USA, was founded in Congressional legislation in 1912 and continues today as one of 90 USDA-Agricultural Research Service locations (Frank 2013). Some of the first research at the NGPRL focused on the ecology and management of native prairie. In 1915, agronomist J. T. Sarvis designed and implemented a stocking rate experiment on 101 ha of northern mixed-grass prairie. The central question of concern was: how many acres of native prairie are necessary to support the growth of a steer during the grazing season (May to October) on a long-term basis (Sarvis 1923)? Part of that original experiment continues today as the longest continuously managed grazing experiment in North American northern mixed-grass prairie.

The objectives of this paper are to (i) document and present the origin, evolution, and scientific outcomes from this 100-yr experiment; (ii) interpret the outcomes in the context of other such long-term studies, and (iii) discuss future directions of this experiment as a part of long-term research networks. We describe the original experiment, summarize the principal results, and then explain the evolution of the experiment within the changing context of the main questions addressed in the late 20th and early 21st century.

MATERIALS AND METHODS

Climate and Ecological Region

The NGPRL is within the temperate steppe ecoregion of the United States, which has a semiarid climate, with yearly evaporation typically exceeding precipitation. Long, cold winters and short, hot summers are typical, with land management characterized by a mixture of dryland cropping systems and livestock production based on rangeland, pastures, and hay production. Average annual precipitation at the site is 414 mm. Average annual temperature is 4°C, though monthly average daily temperatures range from 21 to −11°C. The average frost-free period is 131 d. Gently rolling uplands (0 to 3% slope) characterize the topography. Predominant soil types include Temvik–Wilton silt loams (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). The pastures are on a loamy ecological site (site ID 054XY030ND).

The Original Experiment

Details of the initial design and conduct of the long-term grazing trial are from Sarvis (1920, 1923), Rogler and Haas (1947), and Rogler (1944, 1951). The experiment began in 1915 on 101 ha of native prairie that had been hayed or grazed for some years before but had never been plowed or received seed or fertilizer inputs. Blue grama [*Bouteloua gracilis* (Willd. ex Kunth.) Lag. ex Griffiths], needle-and-thread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth], and prairie junegrass [*Koeleria macrantha* (Ledeb.) J.A. Schultes] along with threadleaf (*Carex filifolia* Nutt.) and needle leaf sedge (*C. duriuscula* C.A. Mey) dominated the vegetation in 1915 (Table 1; Shepperd 1919; Sarvis 1920). Forbs and shrubs present were cudleaf sagewort (*Artemisia ludoviciana* Nutt.), fringed sage (*A. frigida* Willd.), and silverleaf scurf pea [*Pediomelum argophyllum* (Pursh.) J. Grimes].

The 101-ha site was grazed uniformly at a stocking rate of two 2-yr-old steers per hectare in 1915. In 1916, four pastures of 12.1, 20.2, 28.3, and 40.5 ha were established (Fig. 1), and each was stocked with ten 2-yr-old beef steers [initially 0.98, 1.39, 1.83, and 2.4 animal unit months (AUM) ha^{-1}]. Pastures were stocked continuously beginning in mid-May until early to mid-October each year. At times, however, cattle had to be removed early (August or September) from some pastures because forage had run out. The experiment was not replicated; however, the experimental site chosen was uniform in slope, soils, and vegetation. The longevity of the experiment and the use of multiple stocking rates enabled limited statistical analyses.

Two-year-old beef steers were used from 1916 to 1935 because of their common use on ranches (Sarvis 1923). As livestock industry shifts occurred in the 1930s, 2-yr-olds were no longer desired by the markets, so from 1936 to 1940 pastures were stocked with the same number of yearling steers as with 2-yr-olds in previous years. In 1935, there were not enough funds to purchase

Table 1. Baseline vegetation in the native prairie at the Northern Great Plains Research Laboratory in 1915. Species are listed in order of abundance [table adapted from Shepperd (1919) and Sarvis (1920)]. Dominant species were those abundant enough to control plant community processes, primary species were those present at greater than 1% of basal cover but less abundant than the dominant species, and secondary species were those present at less than 1% of basal cover. Modern scientific names follow the USDA PLANTS database (http://plants.usda.gov)

Species	Common name
Dominant	
Bouteloua gracilis (Willd. ex Kunth.) Lag. ex Griffiths	Blue grama
Hesperostipa comata (Trin. & Rupr.) Barkworth	Needle-and-thread
Carex filifolia Nutt.	Threadleaf sedge
Carex inops L.H. Bailey	Sun sedge
Primary	
Artemisia ludoviciana Nutt.	Cudleaf sagewort
Koeleria macrantha (Ledeb.) Schult.	Prairie junegrass
Solidago nemoralis Aiton	Gray golden rod
Pascopyrum smithii (Rybd.) A. Love	Western wheatgrass
Pediomelum argophyllum (Pursh) J. Grimes	Silverleaf scurf pea
Schizachyrium scoparium (Michx.) Nash	Little bluestem
Artemisia frigida Willd.	Fringed sage
Nassella viridula (Trin.) Barkworth	Green needlegrass
Echinacea angustifolia DC.	Purple coneflower
Aristida purpurea Nutt.	Purple three awn
Polygala alba Nutt.	White milkwort
Hesperostipa spartea (Trin.) Barkworth	Porcupine grass
Ratibida columnifera (Nutt.) Woot. & Standl.	Prairie coneflower
Andropogon gerardii Vitman	Big bluestem
Oligoneuron rigidum (L.) Small	Stiff goldenrod
Artemisia campestris L.	Silver sage
Secondary	
Muhlenbergia cuspidata (Torr. ex Hook.) Rydb.	Plains muhly
Liatris punctata Hook.	Dotted blazing star
Calamovilfa longifolia (Hook.) Scribn.	Prairie sandreed
Elymus caninus (L.) L.	Bearded wheatgrass
Bouteloua dactyloides (Nutt.) J.T. Columbus	Buffalograss
Comandra umbellata (L.) Nutt.	Bastard toad flax
Symphyotrichum ericoides (L.) G.L. Nesom	White heath aster
Dalea purpurea Vent.	Purple prairie clover
Dalea candida Michx. ex Willd.	White prairie clover
Lactuca tatarica (L.) C.A. Mey	Blue lettuce
Vicia americana Muhl. ex Willd.	American vetch
Elymus trachycaulus (Link) Gould ex Shinners	Slender wheatgrass
Oxytropis lambertii Pursh	Loco weed
Hedeoma hispida Pursh	Rough false pennyroyal
Salsola kali L.	Russian thistle
Packera plattensis (Nutt.) W.A. Weber & Á. Löve	Prairie groundsel
Machaeranthera pinnatifida (Hook.) Shinners	Lacy tansyaster
Sphaeralcea coccinea (Nutt.) Rydb.	Scarlet globemallow

a full complement of steers for the experiment and therefore not all pastures were grazed. In 1941, the scientists realized that yearlings consumed about 30% less forage than 2-yr-olds and thus they increased stocking rates by 30% (Rogler 1944). Average 3-d weights at the beginning and end of the grazing season were used to calculate cattle gain.

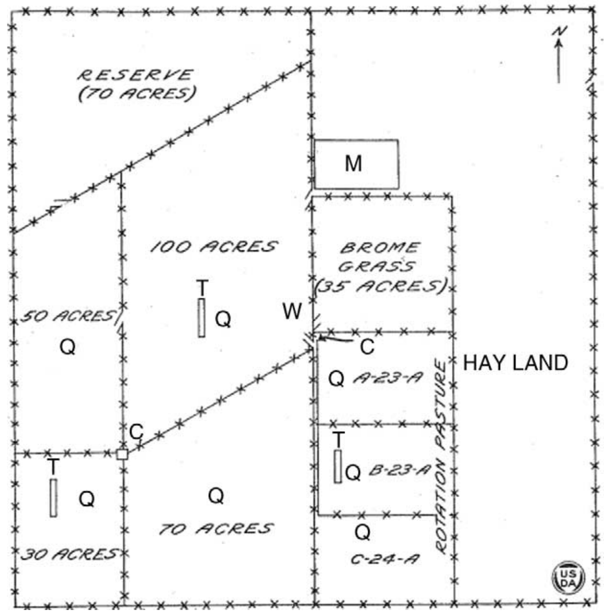

Fig. 1. Drawing of the pasture experiment layout [from Stephens et al. (1925)]. T = grazing exclosure; Q = mapped vegetation quadrat; W = well; C = corrals and water; M = mowing experiment.

Modifications to the Original Experiment

In 1918, a 28.3-ha pasture was added and grazed in a deferred-rotation method in which the steers were rotated among three 9.4-ha paddocks in spring, summer, and fall. Each paddock was rested for two seasons during a 6-yr rotation cycle. The pasture was stocked with thirteen 2-yr-old steers (1.84 AUM ha^{-1}).

The 20.2- and 28.3-ha pastures and the deferred-rotation pastures were discontinued in 1945. The heavily and lightly stocked pastures (12.1 and 40.5 ha, respectively) have been maintained to the present day; however, the size of the pastures has been reduced over the years with concomitant changes in cattle numbers to maintain the relative stocking rates (Table 2).

Vegetation and Soil Measures

Plant species composition was determined intermittently in the early years with the use of species list quadrats (all species identified but not quantified). Beginning in 1938, plants of needle-and-thread were counted in eighty 1-m^2 quadrats per pasture during July and August and counts of junegrass plants along with visual estimates of western wheatgrass tiller density (eighty 1-m^2 quadrats per pasture) began in 1943. Beginning in 1964, point frames (100 frames, randomly located, with 10 pins per frame) were used to estimate canopy cover of vegetation in each pasture during August. Permanent "isolation transects" or grazing exclosures were installed in the lightly and heavily stocked pastures and used for vegetation composition and clipping studies during 1916 to 1945. In August 2011, we used three modified Whittaker

Table 2. Summary of stocking rates, pasture sizes, and management on the four pastures at the Northern Great Plains Research Laboratory, 1916–2014

Period	Pasture size (ha)	Head/ pasture (no.)	Days of grazing (no.)	Stocking rate (AUM ha^{-1})[z]	Cattle type	Breed(s)
Pasture A						
1916–1934	40.4	10	148	0.98	2-yr-old	Mixed
1936–1940	40.4	10	138	0.85	Yearlings	Herefords
1941–1945	40.4	10	147	0.91	Yearlings	Herefords
1946–1950	40.4	13	145	0.90	Yearlings	Herefords
1951–1955	28.3	13	140	1.24	Yearlings	Herefords
1956–1965	28.3	11	140	1.24	Yearlings	Herefords
1966–1983	12.9	3–5	140	0.81	Yearlings	Herefords
1986–2014	15.4	5–6	130	0.63	Yearlings	Herefords/Angus
Pasture B						
1916–1934	28.3	10–12	147	1.39	2-yr-old	Mixed
1936–1940	28.3	10	138	1.22	Yearlings	Herefords
1941–1945	28.3	13	147	1.3	Yearlings	Herefords
Pasture C						
1916–1934	20.2	10	139	1.83	2-yr-old	Mixed
1936–1940	20.2	10	136	1.68	Yearlings	Herefords
1941–1945	20.2	13	147	1.82	Yearlings	Herefords
Pasture D						
1916–1934	12.1	10–12	109	2.40	2-yr-old	Mixed
1936–1940	12.1	10	136	2.81	Yearlings	Herefords
1941–1945	9.4	10	147	3.91	Yearlings	Herefords
1946–1950	9.4	10	122	3.24	Yearlings	Herefords
1951–1955	9.4	10	122	3.24	Yearlings	Herefords
1956–1965	9.4	10	112	2.98	Yearlings	Herefords
1966–1983	2.8	3	93	2.49	Yearlings	Herefords
1986–2014	2.8	3	125	3.35	Yearlings	Herefords/Angus

[z]Animal unit months. One 2-yr-old steer (~340 kg) was considered 0.8 animal units and a yearling steer (~310 kg) 0.75 animal units (Alberta Agriculture and Food 2007).

plots (as in Stohlgren et al. 1995) to assess species richness at a range of spatial scales in the lightly and heavily stocked pastures. All species present within a 20-m by 50-m area of each Whittaker plot were recorded, and percentage canopy cover was visually estimated within ten 1-m^2 quadrats (2 m by 0.5 m) distributed throughout the larger plot. We present plant species composition data from plant counts in quadrats, canopy cover from point frames, and visual estimates of cover from the modified Whittaker plots.

Along with vegetation data, various data on soil electrical conductivity, pH, total C, inorganic C, organic C, and total N data were collected sporadically. Gravimetric soil moisture data were collected from 1919 to 1958 at 15-cm depth intervals to a depth of 1.8 m from the lightly and heavily stocked pastures and in the exclosure.

RESULTS AND DISCUSSION

Animal Performance

In a summary of the first 25 yr, Sarvis (1941) reported that cattle in the heavily stocked pasture had the greatest gain per hectare, whereas cattle stocked at the lowest rate produced the most gain per animal (Fig. 2). The heavily stocked pasture provided 20 to 26 fewer grazing days per year than did other pastures (Table 2). A shortened grazing season may reduce flexibility in grazing management, incur additional feed costs, and compromise the condition of stock (Willms et al. 1986a). Little to no gain, and even weight loss, occurred during October of most years on all pastures regardless of stocking rate (Fig. 3).

Although forage use was not assessed, the amount of foliage cover remaining at the end of the grazing season (visually estimated) during 1916 to 1935 was 51, 74, 93, and 98% (averaged across years) for pastures stocked initially at 2.40, 1.83, 1.39, and 0.98 AUM ha^{-1}, respectively. Foliage cover remaining at the end of the season in 1936 to 1941 averaged 50, 64, 71, and 86% for the same treatments. A primary conclusion at that time was that it required 2.8 ha of prairie to carry one 2-yr-old steer for 5 mo (1.4 AUM ha^{-1}; Sarvis 1941). After continuing the study following Sarvis' retirement in 1941, Rogler (1944) concluded that a stocking rate of one yearling steer to 2.2 ha for 5 mo (1.7 AUM ha^{-1}) gave near maximum gain per head, did not degrade vegetation, and left about 55% foliage cover at the end of the grazing season. Research on native grasslands in Alberta indicated that maintaining an adequate litter amount and cover moderated soil temperature and retained soil moisture (Willms et al. 1986b).

After 25 yr of comparing stocking methods, Rogler (1951) concluded that there was no advantage in terms of animal weight gain to deferred rotational stocking (where one-third of the pasture was rested every third year) compared with continuous season-long stocking. It was noted, however, that deferred-rotational stocking could be beneficial to prairie vegetation by providing

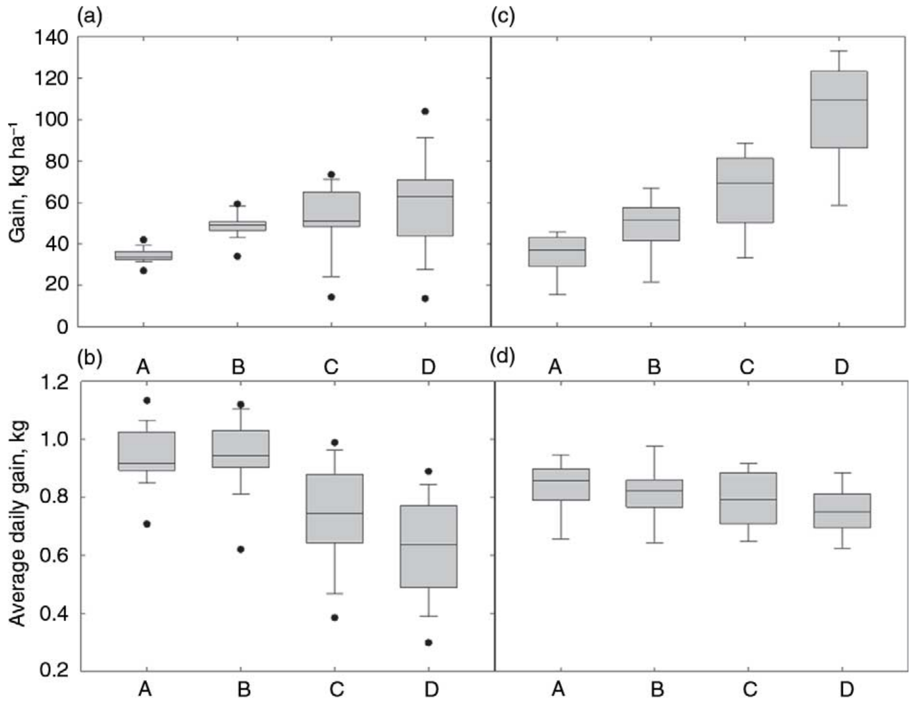

Fig. 2. Liveweight gain of 2-yr-old steers from 1916 to 1934 (2a and 2b; Sarvis 1941) and yearling steers from 1936 to 1945 (2c and 2d; Sarvis 1941; Rogler 1944, 1951) at four stocking rates. Stocking rates 1916 to 1934: A, 0.98 animal unit month (AUM) ha^{-1}; B, 1.39 AUM ha^{-1}; C, 1.83 AUM ha^{-1}; and D, 2.4 AUM ha^{-1}. Stocking rates 1936 to 1945 were A, 0.85 and 0.91 AUM ha^{-1}; B, 1.22 and 1.3 AUM ha^{-1}; C, 1.68 and 1.82 AUM ha^{-1}; and D, 2.81 and 3.91 AUM ha^{-1}. Boxes show the distribution of values from the 25th and 75th percentiles, whiskers indicate the 10th and 90th percentiles, solid line inside the boxes indicates the median value. Individual data points indicate outliers.

rest periods that would allow native grasses to recover from defoliation [see Willms and Jefferson (1993) for an overview]. The rotational stocking implemented in this experiment relied on a rigid schedule of rotation and only a few paddocks, perhaps contributing to the apparent lack of benefit to livestock gain. Contemporary use of rotational stocking often involves many paddocks grazed in a more flexible and adaptive manner that better matches forage demand with forage availability. Furthermore, the availability of modern fencing and watering technology facilitates flexible management of rotational stocking.

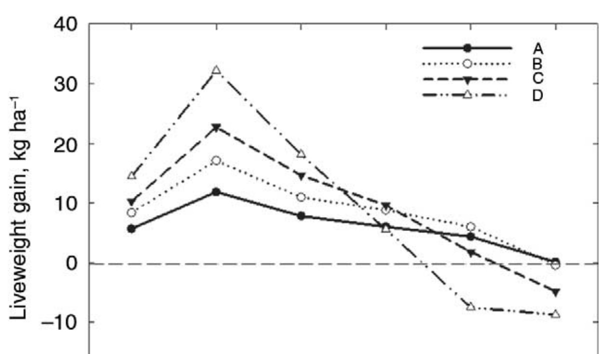

Fig. 3. Seasonal distribution of livestock production from 1916 to 1935 at four stocking rates on native prairie pastures at the Northern Great Plains Research Laboratory; A, 0.98 animal unit month (AUM) ha^{-1}; B, 1.39 AUM ha^{-1}; C, 1.83 AUM ha^{-1}; and D, 2.4 AUM ha^{-1}. Data from Sarvis (1941).

Livestock weight gain data from 1916 to 1945 were used to develop predictive relationships among gain, rainfall, and soil moisture (Fig. 4; Rogler and Haas 1947). Forage and cattle production on native prairie were positively correlated with soil moisture to a 1.8-m depth in the prior fall and with April to July rainfall in the current production year (Rogler and Haas 1947). Summing soil moisture and rainfall into a single value, however, resulted in the best linear relationship. Long-term (1930 to 1983) research on *Hesperostipa–Bouteloua* grassland in Alberta produced similar results indicating precipitation from April to July combined with previous precipitation was highly correlated with forage production (Smoliak 1986). Long-term (76 yr) research on mixed grass prairie at Miles City, Montana, indicated that longer, cooler growing seasons were associated with greater beef calf gains (MacNeil and Vermeire 2012). Recently, Reeves et al. (2014) used a subset (1936 to 2005) of the long-term livestock data from Mandan

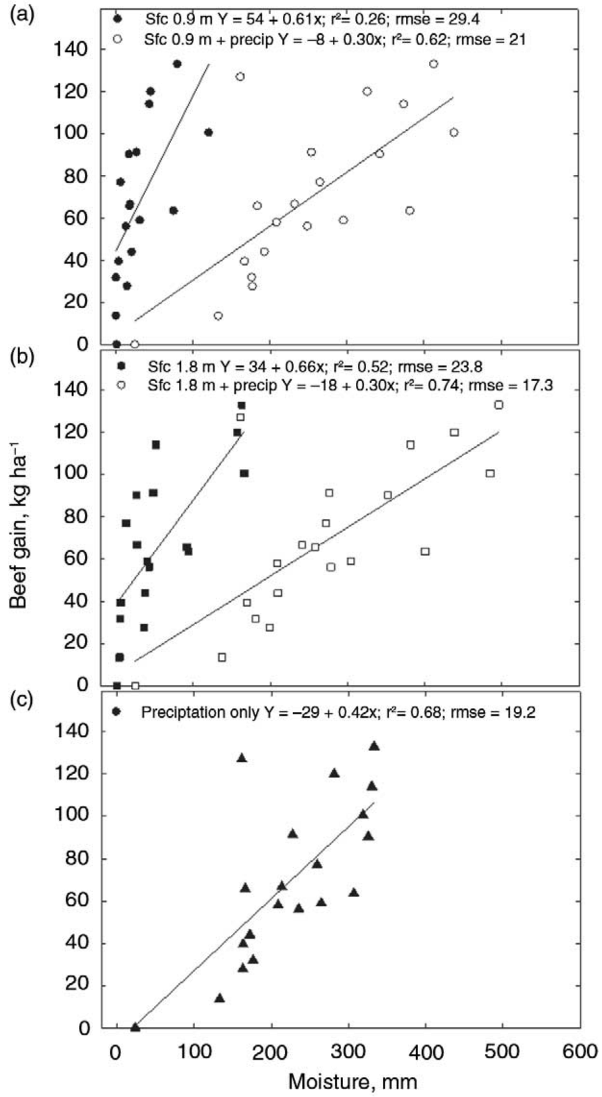

Fig. 4. Livestock production on the prairie pastures in relation to soil moisture in the prior autumn to a 0.9 (5a) or 1.8-m (5b) depth. Solid symbols indicate the relationship for soil moisture only and open symbols the combination of soil moisture and current year precipitation. Livestock production in relation to current year precipitation only is in 5c. Redrawn from data presented in Rogler and Haas (1947).

to examine the effects of spring and summer temperature and precipitation, as well as previous growing season and fall/winter precipitation on cattle production. Seasonal weather variability had a larger effect on cattle production and explained more (higher R^2 and model-averaged coefficients) of the yearly variation in production on the heavily stocked pasture compared with light stocking. The results indicated ranchers could reduce risks from poor seasonal weather conditions by adjusting stocking rates to fit forage production; however, these decisions require timely and accurate forecasts of near-term weather coupled with a production model.

The current stocking rate recommendation for beef cattle, based partly on Mandan research, is a conservative value of 1.2 to 1.7 AUM ha^{-1} on loamy ecological sites in central North Dakota (Biondini et al. 1998; Sedivec and Printz 2012). Livestock gain on the two remaining pastures since 1946 has averaged 45 ($\pm$4.2 standard deviation) kg ha^{-1} and 0.91 ($\pm$0.14) kg d^{-1} for the lightly stocked pasture and 87 ($\pm$13.2) kg ha^{-1} and 0.81 ($\pm$0.18) kg^{-1} d for the heavily stocked pasture. The corresponding number of days grazed on each pasture was 134 ($\pm$20) and 114 ($\pm$28).

Vegetation

More than 275 plant species were identified on the 101-ha experimental site in 1915, of which more than 50 were grasses (Shepperd 1919; Table 1). Forage produced during the grazing season of 1916 was composed of 40 to 50% blue grama and 15 to 20% needle-and-thread (as determined by hand-clipped samples).

Early clipping studies demonstrated that blue grama withstood frequent defoliation, whereas needle-and-thread was very sensitive to defoliation (Fig. 5; Sarvis 1941). Forbs sensitive to heavy stocking included green sagewort (Tarragon; *A. dracunculus* L.), cudleaf sagewort, purple coneflower (*Echinacea angustifolia* DC.), and scurf pea. Both needle-and-thread and junegrass along with the sedges began growth much earlier in spring than blue grama. Needle-and-thread, junegrass, and scurf pea had largely been eliminated from the heavily stocked pasture by the mid-1920s (Stephens et al. 1925). Fringed sage increased from 5 to 25 plants m^{-2} on the heavily stocked pastures during the 1920s and was avoided by cattle, which reduced carrying capacity (Stephens et al. 1925). Fringed sage was less abundant (average of 5 plants m^{-2}) on the lightly stocked pasture during the same period. The abundant bare ground in the heavily grazed pastures may have contributed to the fringed sage invasion by enabling fringed sage seedlings to establish and spread. Fringed sage decreased substantially during the severe drought years in the early 1930s (Sarvis 1941). Data from marked plants indicated that individual fringed sage plants rarely lived more than 6 yr.

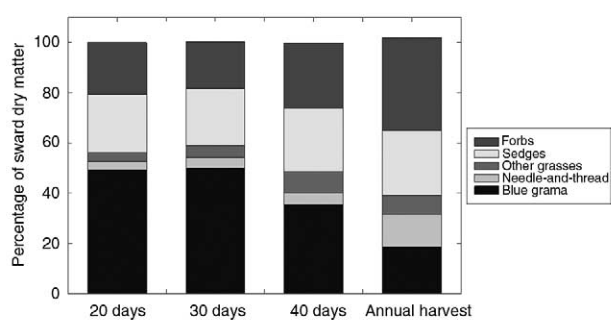

Fig. 5. Botanical composition of dry matter in clipped plots harvested once annually in August or clipped every 20, 30, or 40 d. Data are averages of 18 yr (1917 to 1935; Sarvis 1941).

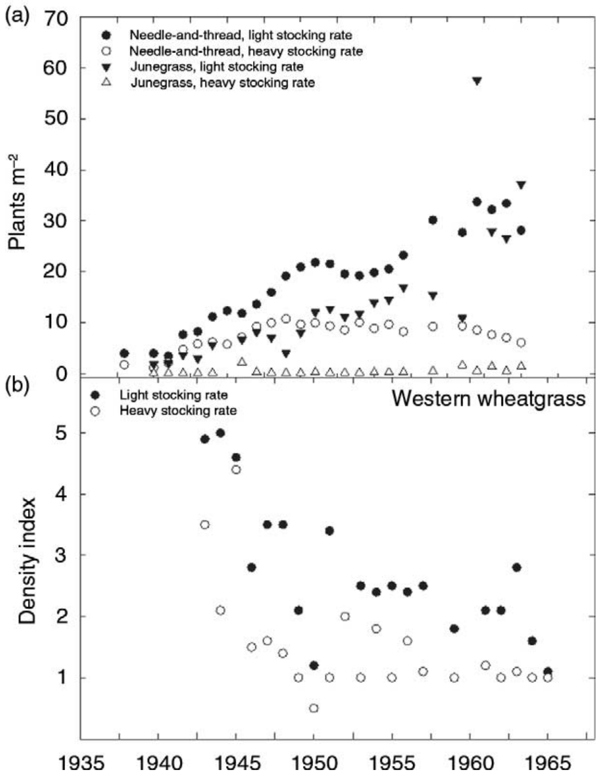

Fig. 6. Changes in plant density of needle-and-thread, prairie junegrass, and western wheatgrass on the lightly and heavily stocked pastures during 1938 to 1965. Data for needle-and-thread and junegrass are averages of plant counts from eighty 1-m^2 quadrats (1a) beginning in 1938. Data for western wheatgrass are averages of visual estimates of tiller density in eighty 1-m^2 quadrats where $1 = 30$ to 40 tillers m^{-2} and $5 =$ 150 to 200 tillers m^{-2} (1b) beginning in 1943. Data taken from unpublished annual reports at the Northern Great Plains Research Laboratory.

During the severe drought of the 1930s, vegetation in all pastures was severely stressed and nearly eliminated in the heavily stocked pasture. In 1936, cattle grazed mostly on forage accumulated and saved from 1935, when there were not enough funds to buy livestock to graze all of the pastures. Drought weakened needle-and-thread, junegrass, little bluestem (S*chizachyrium scoparium* Michx. Nash), sedges, and many forbs. In the early 1940s, however, native plant species such as needle-and-thread, junegrass, and western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve] began to recover (Fig. 6) with the return of adequate rainfall (Fig. 7). Western wheatgrass reportedly replaced needle-and-thread after the 1930s drought (Rogler and Haas 1947). Sarvis (1941) stated that the vegetation damage caused by the Great Drought in 1934 (considered the worst of the last millennium; Cook et al. 2014) and 1936 was initiated by a series of lesser droughts in 1929, 1930, 1931, and 1933 that may have been exacerbated by grasshoppers and high winds in 1933 and 1934. The statewide average Palmer Drought Severity Index

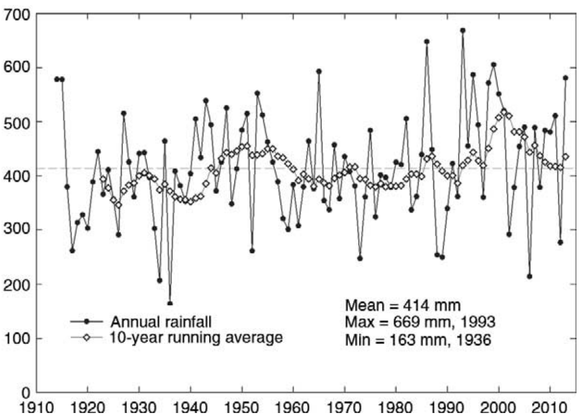

Fig. 7. Annual rainfall at the Northern Great Plains Research Laboratory 1916 to 2014.

(PDSI; an index of meteorological drought) was -1.5 or less (-1.5 indicates moderate drought) during 105 mo between 1930 and 1939 (National Oceanic and Atmospheric Administration 2015). Other multi-year severe droughts occurred in North Dakota from 1958 to 1961, from 1976 to 1977, and from 1988 to 1992 (Williams-Sether et al. 1994).

Vegetation Change and Climate Change

During the 1990s, there was a major change in the vegetation from native grasses (e.g., blue grama, needlegrasses) to dominance by Kentucky bluegrass (*Poa pratensis* L.; Table 3; Fig. 8) in the lightly stocked pasture. In the heavily stocked pasture, dominance by bluegrass did not occur until the early 2000s. Willms and Quinton (1995) reported that Kentucky bluegrass abundance in the seed bank and vegetation increased with greater stocking rate on fescue prairie in southwestern Alberta.

The shift to exotic cool-season grass at Mandan may have been associated with climate change on the Northern Plains during the last century. For example, spring temperatures at Fargo, ND, increased significantly from 1910 to 2010, accompanied by a 12-d increase in the frost-free (0°C) period (Dunnell and Travers 2011). The length of the frost-free period across North Dakota has increased by 0.28 to 2.2 d per decade during the last century (Badh et al. 2009). We hypothesize that drought years in the 1980s (Fig. 7) may have reduced the competitive abilities of native cool-season grasses, and combined with associated shading out of blue grama by Kentucky bluegrass provided the opportunity for Kentucky bluegrass to gain a foothold in the plant community and then subsequently establish dominance. Further, the higher-than-normal precipitation in 15 of the last 24 yr (Fig. 7) along with a longer frost-free period may have provided Kentucky bluegrass with a competitive advantage in early spring and autumn (Toledo et al. 2014). The exact source of the bluegrass propagules is not known; however, herbarium specimens of bluegrass from 1915 exist at NGPRL indicating that bluegrass

Table 3. Analysis of vegetation in the heavy and light stocking rate pastures and an exclosure in August 2011. Data are visual estimates of canopy cover (%) and are means of thirty 1-m^2 quadrats (ten 1-m^2 quadrats in each of three modified Whittaker plots in each pasture) and five 1-m^2 quadrats in the exclosure. T = species present in the 10-, 100-, and 1000-m^2 quadrats of the modified Whittaker plot or in a complete search of the exclosure. Scientific names are according to the USDA PLANTS database (http://plants.usda.gov)

Species	Common name	Heavy	Light	Exclosure
Poa pratensis L.	Kentucky bluegrass	62	52	33
Bromus inermis Leyss.	Smooth bromegrass	1	1	28
Artemisia ludoviciana Nutt.	Cudleaf sagewort	<1	18	5
Medicago lupilina L.	Black medic	12	<1	
Nassella viridula (Trin.) Barkworth	Green needlegrass	3	4	
Oenothera suffrutescens (Ser.) W.L. Wagner and Hoch	Scarlet beeblossom	2	2	3
Antennaria microphylla Rybd.	Pussy toes	3	T	
Taraxacum officinale F.H. Wigg.	Dandelion	2	<1	
Bouteloua gracilis (Willd. ex Kunth.) Lag. ex Griffiths	Blue grama	2	T	
Pascopyrum smithii (Rybd.) A. Love	Western Wheatgrass	2	1	
Artemisia frigida Willd.	Fringed sage	2	<1	
Symphyotrichum ericoides (L.) G.L. Nesom	White heath aster	2	<1	
Oxalis corniculata L.	Woodsorrel	2		
Cirsium undulatum (Nutt.) Spreng.	Wavy leaf thistle	1	3	
Achillea millefolium L.	Yarrow	1	<1	
Lactuca tatarica (L.) C.A. Mey	Blue lettuce	<1	1	<1
Lithospermum canescens (Michx.) Lehm.	Hoary puccoon	<1	<1	
Solidago missouriensis Nutt.	Prairie goldenrod	<1	3	
Vicia americana Muhl. ex Willd.	American vetch	<1	<1	
Dichanthelium oligosanthes (Schult.) Gould	Scribners panicum	<1	<1	
Oligoneuron rigidum (L.) Small	Stiff goldenrod	<1	2	1
Setaria viridis (L.) P. Beauv.	Green foxtail	<1	T	
Solidago speciosa Nutt.	Showy goldenrod	<1	<1	
Sphaeralcea coccinea (Nutt.) Rybd.	Scarlet globemallow	<1		
Polygala alba Nutt.	White milkwort	<1		
Polygonum aviculare L.	Prostrate knotweed	<1		
Artemisia campestris L.	Silver sage	<1		
Agropyron cristatum (L.) Gaertn.	Crested wheatgrass	T	<1	
Amaranthus albus L.	Prostrate pigweed	T	t	
Anemone cylindrica A. Gray	Candle anemone	T	T	
Artemisia dracunculus L.	Tarragon	T	4	
Astragalus crassicarpus Nutt.	Ground plum milkvetch	T		
Asclepias verticillata L.	Whorled milkweed	T	<1	
Carex filifolia Nutt.	Threadleaf sedge	T	T	
Cirsium arvense L. Scop.	Canada thistle	T		
Comandra umbellata (L.) Nutt.	Bastard toadflax	T	T	
Dalea purpurea Vent.	Purple prairie clover	T	T	
Echinacea angustifolia D.C.	Purple coneflower	T	T	
Grindelia squarrosa (Pursh) Dunal	Curly cup gumweed	T		T
Physalis heterophylla Nees	Clammy ground cherry	T		
Polygonum convolvulus L.	Wild buckwheat	T		
Solidago mollis Bartlett	Soft goldenrod	T	T	
Tragopogon dubius Scop.	Yellow salfsify	T		T
Pediomelum argophyllum (Pursh) J. Grimes	Silverleaf scurfpea		4	2
Lotus unifoliolatus (Hook.) Benth.	American birdsfoot trefoil		2	
Symphoricarpos occidentalis Hook.	Snowberry		2	1
Symphyotrichum falcatum (Lindl.) G.L. Nesom	White prairie aster		1	
Aristida purpurea Nutt.	Purple threeawn		1	
Hesperostipa comata (Trin. & Rupr.) Barkworth	Needle-and-thread		<1	T
Lygodesmia juncea (Pursh) D. Don ex Hook.	Skeleton plant		<1	
Bromus arvensis L.	Field brome		<1	
Liatris punctata Hook.	Dotted blazing star		<1	
Zizia aptera (A. Gray) Fernald	Heartleaf alexander		<1	
Amorpha canescens Pursh	Lead plant		T	T
Andropogon gerardii Vitman	Big bluestem		T	
Asclepias syriaca L.	Common milkweed		T	
Calamovilfa longifolia (Hook.) Scribn.	Prairie sandreed		T	
Rosa arkansana Porter	Prairie rose		T	9
Oligoneuron album (Nutt.) G.L. Nesom	Prairie goldenrod		T	
Brickellia eupatorioides (L.) Shinners	False boneset			7
Ambrosia artemisiifolia L	Western ragweed			7
Asclepias hirtella (Pennell) Woodson	Green milkweed			1

Table 3 (*Continued*)

Species	Common name	Heavy	Light	Exclosure
Helianthus pauciflorus Nutt.	Stiff sunflower			<1
Aristida oligantha Michx.	Prairie three awn			<1
Allium ascalonicum L.	Prairie onion			T
Koeleria macrantha (Ledeb.) Schult.	Prairie junegrass			T
Ratibida columnifera (Nutt.) Woot. & Standl.	Prairie coneflower			T
Schizachyrium scoparium (Michx.) Nash	Little bluestem			T

was present at some level on surrounding rangeland pastures at the start of the experiment. The shift in vegetation composition and dominant species has not reduced livestock productivity (Fig. 9); however, invasion by exotic grasses can be detrimental to other ecosystem attributes such as native plant species diversity, water and nutrient cycling, and wildlife habitat (Toledo et al. 2014). Long-term solutions to invasion by bluegrass will likely include adaptive management strategies such as changes in the timing and intensity of grazing to take advantage of earlier forage production and targeted use of fire and herbicides to reduce bluegrass abundance (Hendrickson and Lund 2010).

The long-term experiment demonstrated the resilience of the native mixed-grass prairie in response to the severe drought of the 1930s. Interestingly, it appears the native prairie has not been as resistant to recent climate change involving above-normal rainfall, allowing for invasion by exotic grasses.

After 1945, the focus of research at the NGPRL shifted, and part of the stocking rate experiment was discontinued. The heavily and lightly stocked pastures, however, were maintained.

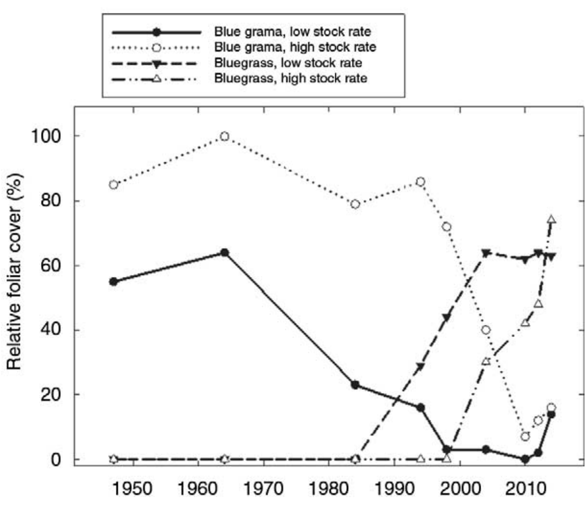

Fig. 8. Relative foliar cover (%) of blue grama and Kentucky bluegrass in lightly and heavily stocked pastures of native prairie near Mandan, ND. Data from 1947, 1964, 1984, and 1994 are from Frank et al. (1995). Data from 1947 are relative foliar cover from visual estimates. Data from 1964 to 2014 are relative foliar cover from point frame measurements (100 10-pin frames per pasture).

A Shift to Soil and Fertilizer Research in the 1950s and 1960s

Increased availability of inorganic fertilizers after World War II prompted new research into native grassland responses to fertilizer addition. In the 1950s and 1960s, there were small-plot fertilizer trials conducted on the lightly and heavily stocked pastures. Plots were fenced from grazing and mechanically clipped. Nitrogen (ammonium nitrate at 0, 34, and 101 kg ha^{-1}) applied for four years in autumn induced earlier spring growth. Moreover, western wheatgrass, which increased in these pastures after the severe drought of the 1930s, responded most to N applications and accounted for most of the yield increase. On the other hand, blue grama did not respond to autumn-applied N (Rogler and Lorenz 1957). Additional long-term research on other sites at the NGPRL confirmed the shift in grass functional group with N fertilization (Lorenz and Rogler 1972, 1973a, b). Consequences of the major shift in vegetation functional group from C_4 to C_3 grass were not further explored; however, research on other grasslands has shown reductions in plant species diversity with increasing fertilization (Gerstner et al. 2014).

In addition to above-ground vegetation responses, studies also addressed the effects of fertilization on soil chemical properties and below-ground biomass. Smika et al. (1961) sampled the Rogler and Lorenz (1957) plots in 1959 after 9 yr of fertilizer treatments. The principal findings were that soil pH of the surface 15 cm of soil decreased from 6.5 in zero-N added plots to 5.9

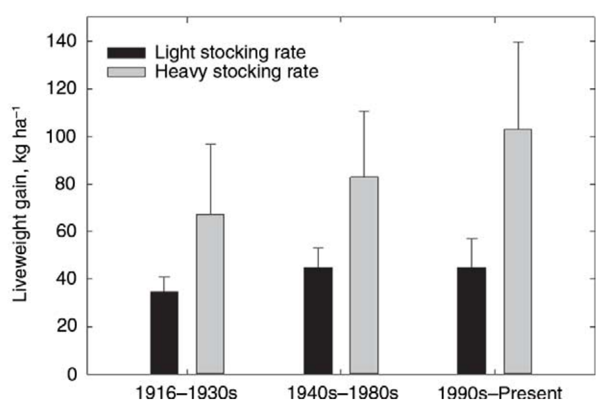

Fig. 9. Steer liveweight gains on the lightly and heavily stocked pastures during three major periods from 1916 to 2012 (from Toledo et al. 2014).

in the high N rate plots with no effect at deeper depths (> 15 cm). Decreases in soil pH were accompanied by an increase in available P. Soil moisture to a 1.8-m depth in fertilized plots was lower than in zero-N added plots, presumably due to greater rooting activity and plant water use in fertilized plots.

Follow-up research addressed fertilizer placement effects on forage productivity (Smika et al. 1963) and grazing and fertilizer effects on root development (Lorenz and Rogler 1967). Subsurface placement (10-cm depth) of N fertilizer increased forage yield more than surface application, presumably because physical disturbance caused by the application method (shallow cultivation) stimulated N mineralization and not necessarily because of the addition of inorganic N (Smika et al. 1963). After 10 yr of fertilizer application, root mass to a 1.2-m depth was greater with N fertilizer than without and the lightly stocked pasture had a greater percentage of root mass below the 15-cm depth than did the heavily stocked pasture (Lorenz and Rogler 1967). Smoliak et al. (1972) measured greater root mass at shallow soil depths (0 to 15 cm) after 19 yr of heavy grazing on *Stipa–Bouteloua* prairie in Alberta. Vegetation change from deeper-rooted needle-and-thread grass and western wheatgrass to the more shallow-rooted blue grama (Coupland and Johnson 1965) under heavy grazing probably accounted for the differences in root distribution. Despite the initial enthusiasm for enhancing rangeland productivity with fertilizer, this practice has not become common in the northern Great Plains, primarily because of economics (Leistritz and Qualey 1975).

Late 20th Century and Early 21st Century: Repurposing of the Original Experiment

The lightly stocked and heavily stocked pastures continued to be maintained under the same management from the 1960s through the 1980s. There was renewed research activity in the 1980s that addressed morphological development of native grasses and remote sensing. In the 1990s and 2000s, scientists took advantage of the long-term history of the pastures to conduct new research on soil change, C balance, and greenhouse gas emissions.

Morphological Development of Cool-Season Native Grasses

In the 1980s, vegetation in the pastures was used to determine morphological development of western wheatgrass, needle-and-thread, green needle grass [*Nassella viridula* (Trin.) Barkworth], and prairie junegrass in relation to air temperature (Frank and Hofmann 1989; Frank 1991; Frank 1996). A simple decision support tool for estimating grazing readiness of native vegetation was developed from empirical relationships between growing degree days (GDD base 0°C) and developmental stage of the grasses (Frank et al. 1993).

Remote Sensing

The heavily and lightly stocked pastures have served as a resource to test and calibrate remote sensing approaches for monitoring vegetation for management purposes. Initial work focused on hand-held radiometric methods for estimated green phytomass or leaf area index (Aase et al. 1987; Frank and Aase 1994). Later efforts focused on using satellite data for landscape-scale measurements of C:N ratios (Phillips et al. 2006) and estimates of forage quality to aid stocking rate decisions on prairie (Beeri et al. 2007; Phillips et al. 2009).

Soil Quality

A series of studies from 1994 to 2014 examined long-term changes in soil chemical and physical properties (i.e., soil quality) of the heavily and lightly stocked pastures. Frank et al. (1995) examined changes in soil C sampled in autumn 1991 and reported that the lightly stocked pasture had 17% less soil C to a 1-m depth than a fenced exclosure, whereas the heavily stocked pasture did not differ from the exclosure in soil C but had more soil C than did the lightly stocked pasture. Analysis of soil ^{13}C levels revealed that 24% of soil C came from C_4 vegetation (presumably blue grama) in the heavily stocked pasture, whereas 20% came from C_4 vegetation in the lightly stocked pasture. It was hypothesized that the greater amount of blue grama in the heavily stocked pasture may have accounted for the greater amount of soil C because blue grama partitioned more assimilated C to below-ground structures as also suggested by Henderson et al. (2004) on mixed-grass prairie in Alberta, Canada.

Wienhold et al. (2001) sampled the same pastures and exclosure in autumn 1997 at 0- to 5-cm and 5- to 15-cm depths to compare physical, biological, and chemical soil properties. Soil bulk density was lowest in the exclosure and highest in the heavily grazed pasture at the 0- to 5-cm depth, but did not differ at 5 to 15 cm. The heavily grazed pasture had higher NO_3-N concentrations along with greater populations of bacteria and actinomycetes than the lightly stocked pasture or exclosure. Microbial biomass C and N were similar among pastures and exclosure. As soil bulk density increased and the relative amount of blue grama in the vegetation increased, the soil quality indicators of total N, organic C, and N mineralization of soil increased.

Liebig et al. (2006, 2014) sampled the lightly and heavily stocked pastures, along with a crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] pasture that had been grazed and received N fertilizer since 1932, to determine grazing management effects on soil nutrient stocks. Trends in soil properties for the two native range pastures were similar to those observed by Frank et al. (1995) and Wienhold et al. (2001). Temporal variation of soil properties within the pastures demonstrated that near-surface soil NO_3-N was greatest at peak aboveground biomass (mid-summer) and soil NH_4-N was greatest in spring (Liebig et al. 2014). Moreover, drought conditions caused a near twofold increase in extractable N in the heavily stocked pasture, but extractable N was stable in the lightly stocked pasture. Soil samples taken from the study before the 1950s unfortunately were not archived. Subsequent soils from various experiments and sampling campaigns in recent years are maintained in a soil archive at NGPRL, including samples collected in 1959 (Liebig et al. 2008a).

Carbon Dioxide (CO_2) Flux

Concern about atmospheric CO_2 concentrations and global climate change in the 1990s spurred new research on CO_2 fluxes and potential C storage in rangelands (Svejcar et al. 1997). Beginning in 1996, micrometeorological methods (Bowen ratio energy balance) were used to quantify CO_2 flux from the lightly stocked pasture (Frank and Dugas 2001). The Mandan site was part of a larger rangeland CO_2 flux network established by the USDA–ARS (Svejcar et al. 1997). Results showed that evapotranspiration and CO_2 flux were greatest in June, which corresponded with peak biomass and leaf area production, and were least in August (Frank and Dugas 2001; Frank 2002). Further work on CO_2 and water vapor flux on the pasture showed that similar fluxes occurred on shrub-invaded prairie (Frank and Karn 2005). After several years of measurements it was concluded that northern mixed-grass prairie was a small sink for C (4 to 67 g CO_2-C m^{-2} yr^{-1} over a 7-yr measurement period), and that dormant-season CO_2 fluxes controlled whether the grassland would become a small sink or source for C (Frank 2004; Fig. 10).

These studies contributed to a larger effort to scale up site measurements to the regional scale via remote sensing and vegetation indices (e.g., normalized difference vegetation index, NDVI; Gilmanov et al. 2005; Wylie et al. 2007). Many of the CO_2 flux studies also contributed to a synthesis of how agricultural practices affect greenhouse gas emissions in the Northern Plains of the United States and the prairies of Canada (Liebig et al. 2005, 2012) as part of the Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) led by the USDA–ARS (Jawson et al. 2005).

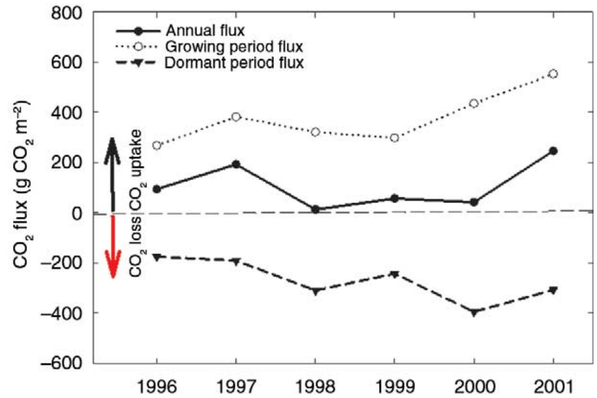

Fig. 10. Annual, growing season, and dormant period fluxes of carbon dioxide from the lightly stocked pasture at the Northern Great Plains Research Laboratory. Data are averages of 6 yr (Frank 2004).

Greenhouse Gases

Scientists at the NGPRL estimated net global warming potential in the two long-term prairie pastures and the aforementioned crested wheatgrass pasture from 2003 to 2006. The team measured soil organic C change and N_2O and CH_4 flux in the pastures, and combined field data with estimates for CH_4 emission from cattle (via enteric fermentation) and CO_2 emissions associated with producing and applying nitrogen fertilizer. Summing across factors, net global warming potential was negative for prairie pastures, implying net removal of greenhouse gases from the atmosphere (Table 4). When data were expressed per unit of animal production (i.e., kg

Table 4. Net global warming potential (GWP) and greenhouse gas intensity (GHGI) for heavily stocked, lightly stocked, and crested wheatgrass pastures at the Northern Great Plains Research Laboratory [adapted from Liebig et al. (2010)]

	Pasture type		
Variable[z]	Lightly stocked	Heavily stocked	Crested wheatgrass
	(kg $CO_{2equiv.}$ ha^{-1} yr^{-1})		
N fertilizer	0*b*	0*b*	259 (0)*a*
Enteric fermentation	176 (28)	484 (76)	563 (227)
CH_4 flux	−63 (9)[y]	−62 (6)	−61 (4)
N_2O flux	520 (85)*b*	477 (39)*b*	1336 (260)*a*
Soil C change	−1416 (193)	−1517 (187)	−1700 (114)
Net GWP	−783 (28)*b*	−618 (76)*b*	397 (227)*a*
	(kg $CO_{2equiv.}$ kg^{-1} animal gain)		
GHGI	−145 (38)*a*	−26 (9)*b*	27 (17)*b*

[z]$CO_{2equiv.}$ emissions associated with enteric fermentation and N fertilizer production and application were derived from the literature. Gas fluxes and soil C change were measured.
[y]Negative values imply net CO_2 uptake.
a, *b* Means in a row with different letters differ ($P \leq 0.05$). Values in parentheses reflect the standard error of the mean.

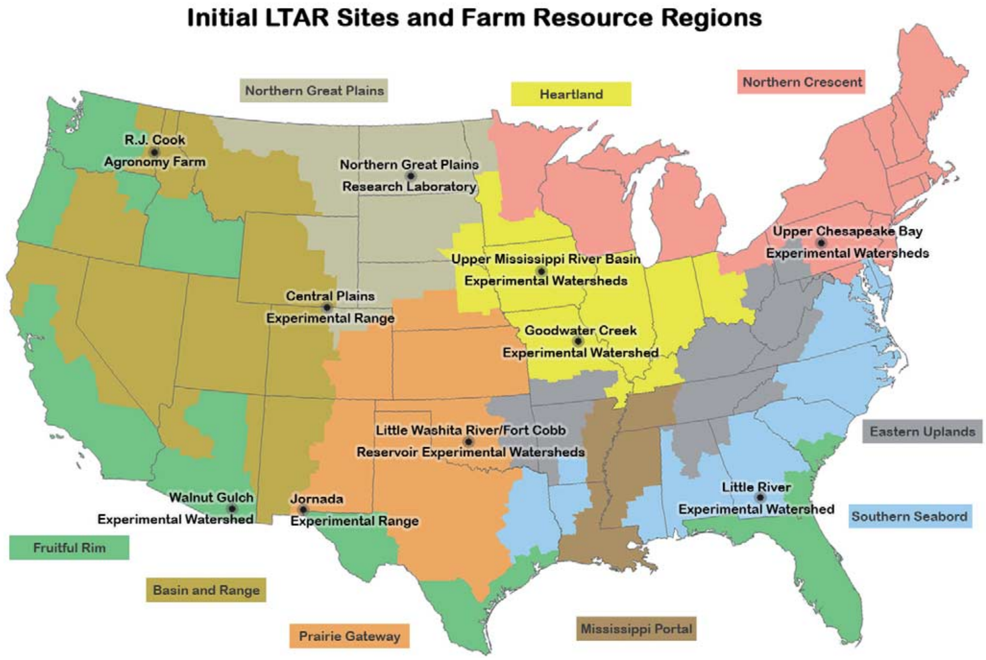

Fig. 11. Location of 18 Long-Term Agro-Ecosystem Research (LTAR) sites in the USA (www.ars.usda.gov/ltar).

$CO_{2equiv.}$ kg^{-1} animal gain) the amount of greenhouse gases removed by the lightly stocked pasture was greater than the heavily stocked pasture, the latter of which did not differ from the crested wheatgrass pasture. While these findings underscored the value of grazed, mixed-grass prairie as a viable agroecosystem to serve as a net greenhouse gas sink in the northern Great Plains, they also highlighted the critical role of stocking rate in regulating the greenhouse gas footprint of meat production from grazed pastures (Liebig et al. 2010).

The prairie pastures were used to test the hypothesis that feeding tannins to cattle would reduce greenhouse gas emissions from livestock urine, as tannins often bind to proteins and reduce N concentration in urine (Kronberg and Liebig 2011). Methane uptake by soil was over 40% less within the tannin urine treatment as compared to normal urine, and may have been repressed by the capacity of tannin to bind monooxygenases responsible for CH_4 oxidation. Despite a 34% reduction in N in the tannin urine treatment, no differences in N_2O emission were observed between tannin and normal urine treatments. Collectively, study results suggested the use of tannin as a dietary amendment for livestock did not confer greenhouse gas benefits in the short-term (Liebig et al. 2008b).

Liebig et al. (2014) related soil surface properties within the prairie pastures to CO_2, CH_4, and N_2O GHG fluxes and found electrical conductivity was most frequently associated with fluxes over a 3-yr period. As in situ measurements of electrical conductivity can be done with relative ease, such measurements were proposed as a screening tool for identifying potential greenhouse gas ‘‘hotspots’’ in grazingland.

LOOKING FORWARD

The present time interval has been termed the ‘‘anthropocene’’ in which many of the earth’s processes and systems have been radically changed by humans (Crutzen 2002). Learning how to cope with and adapt to these profound changes will require continuing and new long-term research. Both the USDA and the National Science Foundation recognized the need for long-term agricultural and ecological research by the formation of two national networks. The long-term pastures at Mandan will continue to serve as a unique resource for generating new knowledge via these long-term agricultural and ecological networks.

Long-Term Agro-Ecosystem Research Network (LTAR)

In 2011 and 2014, the USDA organized 18 USDA–ARS, university, and nongovernmental organization research sites across the United States into the Long-Term Agro-Ecosystem Research (LTAR; www.ars.usda.gov/ltar) network. The network will conduct long-term, transdisciplinary science to address challenges associated with sustainable agricultural intensification (Walbridge and Shafer 2011). The NGPRL was chosen as one of the initial network sites in 2011. The LTAR network will organize and enhance existing research infrastructure into a coordinated network of research platforms in representative agricultural landscapes across the United States (Fig. 11).

This national network will develop an understanding of how to sustain or enhance agricultural production at the watershed/landscape scale to meet increasing demands for agricultural goods and services against a background of climate change. The LTAR network includes several long-term grazingland research sites that will continue to contribute important new information on the soils, vegetation, and ecosystem services of these systems. The long-term prairie pastures at NGPRL will be incorporated into new multi-location research as part of the network. The data archive will also contribute to cross-location retrospective analyses and syntheses.

National Ecological Observatory Network (NEON)

In 2008, the NGPRL was chosen to be one of the National Ecological Observatory Network (NEON) sites (www.neoninc.org). The NEON network provides research infrastructure to support continental-scale ecological research within specific domains located in the United States (Lowman et al. 2009). Research sites are geographically distributed to represent ecosystems ranging from rain forests to high deserts. Mandan was selected as an agricultural land-use site within the Northern Plains Domain. In 2013, construction began on an instrumentation tower in the lightly stocked pasture and the site will be fully instrumented and operational in 2017.

SUMMARY

A century ago, a small group of scientists had the foresight to establish what has become one of the longest-running grazing experiments in North America. The original question was very practical (e.g., how many acres does it take to support a steer during the grazing season?). The stocking rate recommendation resulting from this research was one 2-yr-old steer per 2.8 ha (1.4 AUM ha^{-1}) or one yearling steer per 2.2 ha (1.7 AUM ha^{-1}) for May to October. The recommended stocking rates resulted in abundant forage in favorable growing seasons and sufficient forage in difficult growing seasons to feed steers without overgrazing or damaging the vegetation. The research provided some of the first information on the forage and livestock productivity of northern mixed-grass prairie to enable better management by ranchers. For example, it was demonstrated that both forage production and livestock gain were greatest in May and June, which were associated with prior autumn soil moisture and the amount and timing of rainfall. In addition to the practical information generated, the experiment produced some of the first data on the ability of native grasses to withstand grazing, the critical role of soil moisture in maintaining rangeland productivity, and applied ecological insights on the persistence and resilience of native prairie during the worst drought of the last millennium. The foresight and perseverance of many scientists ensured that these long-term pastures continue to serve as a unique resource to address new 21st century questions dealing with drought, soil quality, greenhouse gas emissions, invasive species, and climate change.

ACKNOWLEDGEMENTS

Johnson Thatcher Sarvis established the experiment in 1915 and managed it until 1940. The experiment was continued by George Rogler from 1940 to 1952. Russell Lorenz and G. Rogler continued the experiment from 1953 to 1973. R. Lorenz managed the experiment from 1974 to 1979. The experiment was continued by Lenat Hofmann from 1980 to 1992. Jim Karn managed the experiment from 1993 to 2002. Numerous technicians and part-time students were also involved in the day-to-day management and conduct of the experiment. We would like to recognize these scientists and support staff for their extraordinary foresight and determination in skillfully managing and continuing this experiment into the 21st century.

Thanks also to Holly Johnson at the NGPRL for organizing, cataloging, and annotating the publications from the long-term experiment. A complete list (and electronic copies) of scientific publications generated from this experiment is available at http://www.ars.usda.gov/Research/docs.htm?docid=25311.

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