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Original Research

Vegetation and Animal Performance Responses to Stocking Density Grazing Systems in Nebraska Sandhills Meadows☆

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A B S T R A C T

Management-intensive grazing, which is proposed to increase forage and animal productivity and maintain soil integrity and biodiversity, is seen as an alternative to meet 21st century agricultural and environmental challenges. The purpose of this study was to test the hypothesis that high levels of trampling of standing vegetation associated with mob grazing (a.k.a., ultrahigh stocking density) leads to increased plant diversity and productivity. A long-term experiment was established on a subirrigated meadow in the Nebraska Sandhills as a complete block design comparing three grazing treatments applied annually during the growing season for 8 consecutive yr (2010–2017): 120-pasture rotation with one grazing cycle (mob; 225 000 kg live weight ha^{-1}), four-pasture rotation with one grazing cycle (4PR1; 7 000 kg live weight ha^{-1}), and four-pasture rotation with two grazing cycles (4PR2; 5 000 kg live weight ha^{-1}). All treatments were set at a moderate stocking rate (7.4 animal unit months ha^{-1}) using yearling steers. Percentage trampling, plant production, species composition, and steer weight gain were estimated annually. We applied linear mixed-effect models to account for year and treatment effect on the response variables. Percentage trampling on mob pastures ranged from 40% to 55% over the 8 yr of the study, nearly double that of the 4PR1 and 4PR2 pastures. We observed that mob grazing had no overall effect on plant species composition, aboveground production, and root growth relative to low stocking densities. Average daily gain of steers in the mob pastures was less than gain of steers in 4PR2 pastures in all years, with intermediate weight gains for the 4PR1 steers. Overall, stocking density did not appear to be a driver of plant composition and productivity in rotationally grazed pastures on subirrigated meadows in the Nebraska Sandhills.

Introduction

Increasing the intensity of use and management of grazing lands is seen as a primary means of meeting the world's growing demand for livestock meat and milk (FAO 2011). Increasing livestock production per unit of land area without negatively impacting biodiversity of species and soil integrity has been identified as one of the greatest agricultural and environmental challenges for the 21st century (Shukla et al. 2019; Henchion et al. 2021). However, others have reported that intensification of production from grazing lands to increase plant diversity and to improve soil properties is possible (Gompert 2010; Peterson et al. 2013). Stocking density on smaller pastures with rotation has been identified as a management-intensive tool for the long-term enhancement of soil and for increased forage and livestock production (Matches 1992; Becker et al. 2017) and is commonly associated with short-duration grazing and other management-intensive grazing methods (Savory 1988; Tracy and Bauer 2019). Stocking rate and stocking density

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are commonly adjusted by land managers according to management objectives and strategies. Stocking rate refers to the relationship between the number of animals and the grazing management unit used over a specified time period, whereas stocking density is the relationship between number of animals and the specific unit of land being grazed at a point in time (SRM 1998). While stocking rate is widely advocated as one of the most important management tools, stocking density is largely understudied and its importance in driving outcomes of soil-plant-animal interactions needs further investigation.

Beginning in the 1980s (Savory 1991), stocking density was increasingly cited as a management tool that could be manipulated in intensively managed rotational techniques/systems for improving distribution of grazing and animal wastes and increasing forage production, plant diversity, harvest efficiency, rate of nutrient cycling, and soil health (Tainton 1996; Gompert 2010; USDA/NRCS 2011; Peterson et al. 2013; USDA/NRCS 2016). Achieving optimum levels of these outcomes has been reported to require ultrahigh stocking densities from 50 000 to 200 000 kg live weight ha^{-1} (Tracy and Bauer 2019) to > 200 000 kg live weight ha^{-1} (Peterson et al. 2013) and is commonly referred to as mob grazing. However, in practice, mob-grazing application can be variable and difficult to define even among practitioners. Gurda et al. (2018) reported that four basic characteristics stand out: 1) increased stocking density (56 000 kg ha^{-1} to nearly 1 120 000 kg ha^{-1}), 2) shortened grazing events (usually herds are moved between pastures 1−3 × /d), 3) increased rest periods length (20- to 80-plus d), and 4) more trampled forage.

Perceptions of the purposes and outcomes of mob grazing differ among practitioners and advisors. Survey studies have captured ranchers' impressions and motivations in applying intensive rotational approaches (Roche et al. 2015; Becker et al. 2017). According to Roche et al. (2015), rotational grazing is the dominant grazing management strategy used by ranchers responding to a survey in California and Wyoming; however, only 5% of respondents used management-intensive rotational grazing on rangelands. Becker et al. (2017), focusing on ranchers' perceptions of impacts of ranch-scale multipaddock grazing in north central Texas, observed that ranchers considered the length of nongrazing periods between grazing periods associated with number of pastures as the primary driver of land sustainability indicators. In addition, Peterson et al. (2013) argued that implementation of management-intensive grazing with higher stocking densities and longer recovery periods improve the spatial uniformity of utilization, including trampling and consumption, of pasture vegetation. Reports from many surveys (Gompert 2010; Gurda et al. 2018) emphasize the practitioners' perceptions that the trampling of vegetation not consumed by grazing livestock is a critical characteristic of mob grazing because the trampled vegetation is a major input to the pool of soil organic matter. In fact, the trampling of aboveground vegetation has been proposed to be the principal benefit of mob grazing, resulting in increased soil organic matter and increased rates of nutrient cycling leading to greater soil depth and quality and then greater plant diversity and production (Gompert 2010; Peterson et al. 2013). Scientific evidence of this is limited. Few replicated studies have been conducted on mob grazing approaches, and the replicated studies have been insufficient in length (2 or 3 yr) to test hypotheses concerning the abovementioned outcomes. Furthermore, scientific literature reporting on mob grazing does not document levels of trampling and associated changes in soil and vegetation characteristics. Studies more commonly report on mob grazing as a means of 1) controlling undesirable shrubs (Bailey and Brown 2011; Mesléard et al. 2017) and exotic species (James et al. 2017), 2) manipulating proportions of C_3 and C_4 plants in a management unit (Hickman et al. 2004), and 3) improving distribution of grazing and evenness of utilization of vegetation cover (Barnes et al. 2008; Norton et al. 2013; Reed et al. 2019). Animal performance in a mob grazing system is commonly reported to be less than on less intensively managed pastures (simple rotationally and continuously stocked pastures) (Hawkins 2017; Tracy and Bauer 2019; Augustine et al. 2020), likely because of extremely high grazing pressure and consumption of lower-quality forage (Tracy and Bauer 2019).

The purpose of this study was to test reports that the high level of trampling of standing vegetation associated with mob grazing leads to increased plant diversity and productivity. Proponents of mob grazing report that even grazing distribution, high levels of trampling of standing vegetation, and the short grazing periods characteristic of ultrahigh stocking densities promote soil formation and soil C content, which favors plant diversity and highly productive native plants (e.g., Peterson et al. 2013; Tracy and Bauer 2019). To enhance the likelihood of detecting trampling effects, we designed the study to maximize the amount of trampling by initiating grazing in mid-June when the dominant cool-season grasses in a subirrigated meadow of the Nebraska Sandhills were in the elongation to reproductive stages of growth. The Sandhills region is the largest stabilized sand dune formation in the western hemisphere, providing forage supply for 43% of Nebraska's beef cattle production (≈1.9 million cows, fourth in the United States [NASS 2017]), and multiple other ecosystems services. The high water table positively affects forage production (Stephenson et al. 2019), and the dominance of cool-season grasses contributes to extending the grazing season (Adams et al. 1994; Schacht et al. 2000), which could potentially support increased stocking density under reduced erosion rates when compared with upland sites. The main objective of this study was to compare the plant composition, aboveground plant production, root growth, percentage trampling, harvest efficiency, forage quality, and livestock performance patterns on a Nebraska Sandhills subirrigated meadow managed with mob grazing at an ultrahigh stocking density and two simple rotational grazing systems at relatively low stocking densities.

Methods

Study area

The study was conducted at the University of Nebraska-Lincoln Barta Brothers Ranch (11 km northwest of Rose, Nebraska; 42.22ºN, 99.64ºW, 765 m above sea level), a 2 350-ha ranch with topography, soil, climate, and vegetation typical of the eastern Nebraska Sandhills (MLRA 065-X). Our experiment was established on a subirrigated meadow with a slope < 3% and with groundwater within 45−90 cm of the soil surface most of the year. Soils are sandy loams and mesic Aquic Ustipsamments and mixed, mesic Typic Psammaquents (USDA 2010). The area has a semiarid climate, with a mean annual temperature of 5°C and mean annual rainfall of 571 mm (HPRCC, http://www.hprcc.unl.edu/). The average annual precipitation collected at Barta Brothers Ranch for the study yr (2010−2018) was 612 mm (Fig. 1). About 75% of annual precipitation occurred during the growing season (April through September). The yr 2010−2018 were highly variable in terms of precipitation. Growing season and total precipitation in 2010−2011 and 2016−2018 were above average, while 2012 was an atypically dry yr (see Fig. 1). Average temperature at the ranch for the study period was 17.5°C during the growing season and 9°C annually.

"Non-native cool-season grasses dominate Sandhills meadows, in association with relatively few native warm-season grasses, forbs, sedges (*Carex* spp.), and rushes. Among the main cool-season grasses are the non-native quackgrass (*Elymus repens* [L.] Gould), timothy (*Phleum pratense* L.), Kentucky bluegrass (*Poa pratensis* L.), and native reed canarygrass (*Phalaris arundinacea* L.). The plant

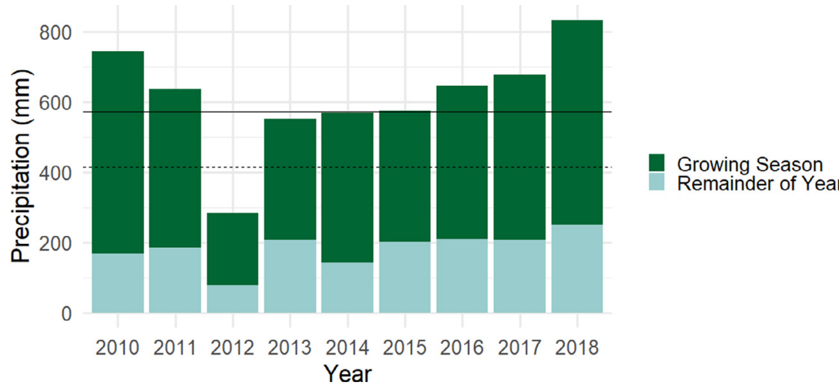

Fig. 1. Annual precipitation from April through August and total annual precipitation from 2010 to 2018. *Black dashed line* is the average growing season precipitation data. *Straight black line* is the average annual precipitation data (1981–2010; High Plains Regional Climate Center, http://www.hprcc.unl.edu/).

Table 1
Summary of applied grazing systems and broad description of the sample design, as well as the average and standard deviation of selected variables after 8 yr of treatment. Treatments: mob (ultrahigh stocking density): 120-pasture rotation with one grazing cycle, 4PR1: 4-pasture rotation with one grazing cycle, and a 4PR2: 4-pasture rotation with two grazing cycles.

Treatments	No. of pastures/unit	Individual pasture size (ha)	Grazing cycles	Grazing season duration (d)	Grazing start date	Stocking density (kg live weight ha^{-1})	No. of animals	Grazing period length (d)
Mob	120	0.06	1	60	Mid-June	225 000	36	0.5
4PR1	4	0.4	1	60	Mid-June	7 000	9	15
4PR2	4	0.6	2	80	Late-May	5 000	10	10

community is also comprised of non-native legumes, such as red clover (*Trifolium pratense* L.) and white clover (*T. repens* L.) (Schacht et al. 2000). The study site had previously been hayed in July over the past several decades.

Experimental design and management treatments

We conducted the field experiment from late May to mid-August for 8 yr, from 2010 to 2017, on a 25-ha subirrigated meadow site, subdivided into two blocks with three grazing treatments each. Final measurements of plant composition and biomass production were taken in 2018, the growing season following the last application of grazing treatments. The treatments were rotational grazing systems that differed by stocking density and number of grazing cycles per year, namely a 120-pasture, ultrahigh stocking density system with one grazing cycle (mob), a 4-pasture rotation system with one grazing cycle (4PR1), and a 4-pasture rotation system with two grazing cycles (4PR2). A cycle constitutes a full progression through a set of pastures over the course of a grazing season. To avoid confounding the effects of stocking rate and stocking density, all treatment pastures were stocked at 7.4 animal unit months (AUM) ha^{-1}, the recommended rate for subirrigated meadows (Volesky et al. 2004). Pastures were stocked with Angus-based yearling steers *(Bos taurus)* with an average initial weight of 365 kg (Table 1). The animal unit equivalent (AUE) was calculated as 0.81 AU (an AU = 450 kg).

The grazing season for the mob treatment was initiated each year in mid-June when the dominant cool-season grasses were at the elongation to reproductive stages of development. At the time of initiation of the study (2010), common justification for mob grazing was that trampled vegetation would be rapidly decomposed by soil microbes, added to soil organic matter, and significantly increase the plant productivity of the site (Gompert 2010). With our objective of testing this, we initiated grazing when conditions for trampling would be optimum with stemmy, upright plants dominating the vegetation cover. The 4PR1 treatment had the same grazing start date as the mob treatment so that comparison between the two treatments would not be affected by different grazing start dates. The 4PR2 treatment with a late May starting date was included to represent a grazing system more commonly recommended to optimize use of relatively high-quality vegetative forage.

Stocking density for the mob treatment was set at 225 000 kg live weight ha^{-1} with a goal of high levels of trampling of standing vegetation (as much as 60%) as expected of mob grazing (Gompert 2010; Peterson et al. 2013). Thirty-six yearling steers were moved twice daily through the 120 pastures (0.06 ha each) over a 60-d grazing season from mid-June to mid-August. Portable electric fences delineated the pastures in the mob treatment, whereas the other treatment pastures had permanent electric fences (see Table 1). Water and trace-mineral salt were moved with the cattle as they were moved from pasture to pasture. Each mob experimental unit was divided into four quadrants (with 30 pastures per quadrant). In each grazing season, a different quadrant was systematically chosen as the starting point.

The 4PR1 treatment had four 0.4-ha pastures grazed by 9 steers for 15 d each, resulting in a 60-d grazing season (from mid-June to mid-August). The 4PR2 treatment had four 0.6-ha pastures with each grazed for 10 d in each of two cycles, resulting in an 80-d grazing season (late May to mid-August). Similar to the mob treatment, a different pasture was systematically chosen as the starting point each grazing season. The three grazed treatments ended on the same date in mid-August in each year. Stocking density was 7 000 and 5 000 kg live weight ha^{-1} for 4PR1 and 4PR2, respectively (see Table 1). In both 4PR1 and 4PR2 treatments, fresh water and trace-mineral salt were always available to the steers.

Vegetation sampling

Frequency of occurrence

The modified-step point method (Owensby 1973) was used in early to mid-June annually from 2010 through 2018 to arrive at estimates of ground cover and frequency of occurrence of plant species in each experimental unit. Sampling points were randomly distributed throughout each experimental unit while avoiding areas within 4.5 m of the fences. Annually, we sampled 300 points per experimental unit of the mob treatment, 600 points per experimental unit of each of the 4PR1 and 4PR2 treatments. To effectively deal with the disparities in sampling effort among treatments, we expressed species composition as proportions of the total number of samples taken in each experimental unit, as suggested by Tuomisto (2010).

At each step point, we recorded two pieces of information: 1) ground cover including litter (L), bare ground (BG), and plant base (PB) and 2) plant species found at the point or, when there was not a plant base at the point, the plant species nearest to the point within a 180-degree arc in front of the point. All scientific plant names follow the Integrated Taxonomic Information System (http://www.itis.gov) and families (APG IV 2016). We classified the plants in functional groups according to source (native or exotic), life cycle (annual or perennial), plant life form (erect forb, rosette forb, vine forb, bush forb [i.e., low plant with many branches that arise from or near the ground, e.g. *T. pratense* L. and T. *repens* L.], decumbent forb, stoloniferous graminoid, rhizomatous graminoid, or bunch graminoid), and, specifically for the Poaceae species, as cool or warm season. We calculated the relative frequency of the plant functional groups and most abundant species, which were considered good descriptors of plant community response to grazing management effect.

Trampling, harvest efficiency, and utilization

We estimated percentage trampling and harvest efficiency by the difference method on the basis of standing biomass of pairs of quadrats placed inside and outside exclosures. Before steers entering a 4PR1 or 4PR2 pasture, ten 1-m^2 exclosures were placed randomly in the pasture. On the day cattle were removed from the pasture, a 0.25-m^2 quadrat was placed in the middle of each exclosure and another one was placed 1 m to the north of each exclosure. Standing vegetation in quadrats placed in exclosures was clipped at ground level and sorted into standing live and standing dead categories and placed in separate paper bags. Litter was also collected from the soil surface and placed in a paper bag. Harvest of vegetation in quadrats outside the exclosures followed the same protocol as inside the exclosures, except trampled vegetation was also collected. Trampled vegetation was detached or attached, current year's shoots that were on or near the soil surface. Trampled attached shoots were identified as being visibly "kinked" and at a $< 45°$ angle to the soil surface. In each quadrant of the mob units, ten 0.25-m^2 quadrats were placed down the center of the 14th or 15th pasture the day before occupation and clipped using the same protocol as in exclosures of the 4PR1 and 4PR2 quadrats. On the day following grazing, a 0.25-m^2 quadrat was placed 1 m north of each pregraze quadrat location and clipped using the same protocol as outside the exclosures of the 4PR1 and 4PR2 quadrats. All bagged samples were dried in a forced-air oven at 60°C to a constant weight and the weight was recorded. Measurements started in the second half of May and finished the first half of August in 2010, 2013, 2014, 2015, and 2017. 4PR1 and mob treatments had four clipping dates per growing season, performed every 15 d, while 4PR2 had eight clipping dates, because of the two grazing cycles, performed every 10 d. Estimates of tramping, harvest efficiency, and utilization were calculated as follows:

$$\text{Trampled}(\%) = \left(\text{T} \div \text{SL}_{\text{nongrazed}}\right) \cdot 100 \quad (1)$$

$$\text{Harvest Efficiency}(\%) = \left[\left(\text{SL}_{\text{nongrazed}} - \text{SL}_{\text{grazed}} + \text{T}\right) \div \left(\text{SL}_{\text{nongrazed}}\right)\right] \cdot 100 \quad (2)$$

$$\text{Utilization}(\%) = \left[\left(\text{SL}_{\text{nongrazed}} - \text{SL}_{\text{grazed}}\right) \div \left(\text{SL}_{\text{nongrazed}}\right)\right] \cdot 100 \quad (3)$$

where T = weight of trampled vegetation, $SL_{nongrazed}$ = weight of standing live vegetation not exposed to grazing, and SL_{grazed} = weight of standing live vegetation exposed to grazing. With the paired quadrats, standing live biomass in the nongrazed quadrat was less than the standing live biomass in the grazed quadrats about 5.6% of the time. We excluded these data points from data analysis.

Aboveground plant production

From 2012 to 2018, aboveground vegetation biomass was estimated annually. Ten 1-m^2 exclosures were placed in each experimental unit in early May each year. In the 4PR1 and 4PR2 treatments, two or three exclosures were placed randomly in each pasture per experimental unit. In the mob treatment, two or three exclosures were placed randomly in each quadrant of a mob-grazed experimental unit. In mid-August of each year, vegetation was clipped at ground level in a 0.25-m^2 quadrat placed in the middle of each exclosure. The vegetation was sorted into standing live, standing dead, and litter categories, and each category was bagged accordingly. Shortly after collection, we dried the samples in a forced-air oven at 60°C to a constant weight, which was then recorded. We removed from the dataset 0.75% ($n = 5$) of the samples before analysis, for being extreme values and identified as outliers. Numbers that were beyond 1.5 × the interquartile range were considered outliers.

Annual net root growth

In-growth root cores were established in each experimental unit of the mob and 4PR1 treatments in 2012 and 2013. In each experimental unit of these treatments, 12 soil cores (15 cm deep and 5 cm in diameter) were taken in early May of each year using a bucket auger. Each core location was flagged, and its GPS location was recorded. Soil from the cores was separated into the top 7.5-cm and bottom 7.5-cm portions on removal and dried at 60°C in a forced-air oven for a minimum of 12 h. Once dry, the soil was sieved through 1.4- and 1-mm screens to remove existing root material. Two-mm plastic mesh cylinders were placed in each of the augured holes (with the capped end at the bottom of the hole) and filled with the sieved soil in mid-May 2012 and 2013 at a bulk density similar to the surrounding soil. The cylinders were retrieved in late October using a knife to separate the core from the surrounding soil and roots. Roots growing into the core were trimmed as close to the mesh as possible before placing the core in a plastic bag. Retrieved cores were placed in frozen storage until root processing occurred. The first step involved laying the thawed core on a tray and hand separating the larger roots from the soil. The soil was then sieved through a series of 10 (2-mm), 14 (1.4-mm), and 18 (1-mm) sieves to capture most of the smaller roots. In the final step, the soil was placed and gently agitated in a water bath, resulting in the fine roots floating to the surface, where they were removed with tweezers. This process was considered effective in recovering roots because the remaining soil mass was < 5% organic matter. Organic matter content of "cleaned" soil samples were periodically determined using a muffle furnace (combusted at 600°C). After root mass samples had been washed, they were placed in a forced-air oven at 50°C for 48 h and weighed to the nearest 0.0001 g.

Forage quality

Forage quality of the standing live herbage collected through the grazing season outside the exclosures in 4PR1 and 4PR2 pastures and the day after grazing in the mob pastures was quantified in 2010, 2011, 2013, and 2017. Following drying and weighing

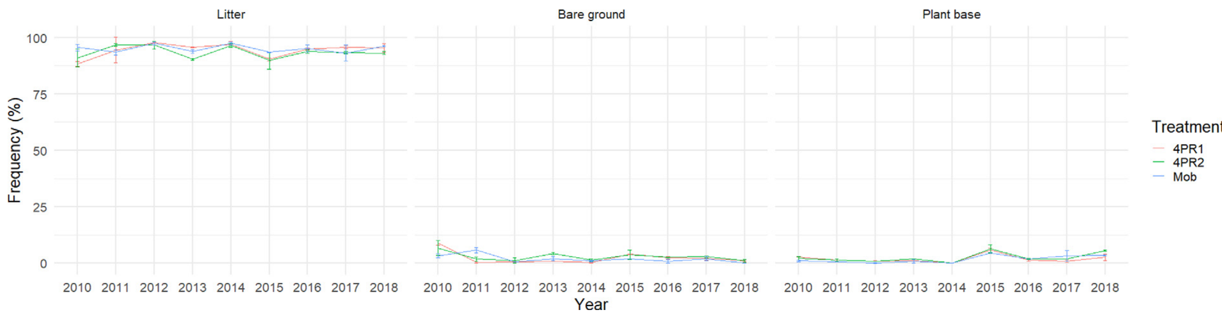

Fig. 2. Percentage ground cover by litter, bare ground, and plant base over the 8 yr of the study and three rotational grazing systems (mob: ultrahigh stocking density, 4PR1: four-pasture rotation with one grazing cycle, 4PR2: four-pasture rotation with two grazing cycles) in the Nebraska Sandhills meadows.

of the clipped samples (see Trampling, harvest efficiency, and utilization), four samples of standing live herbage were selected randomly from the 10 clipped samples in each pasture during each of the following five time periods: midspring (May 21–June 5), late spring (June 6–June 21), early summer (June 22–July 7), midsummer (July 8–July 23), and late summer (July 24–August 8). The four samples were divided into two pairs of samples, which were composited and ground through a 1-mm screen using a Wiley mill. The ground samples were analyzed for nitrogen (N) content on a dry matter basis. Nitrogen analysis was conducted with a LECO FP-528 N analyzer using standard methods (AOAC 1996). Nitrogen content was multiplied by 6.25 to arrive at estimates of crude protein content (CP).

Animal performance

The steers used in this study were transported by truck each year to the study site from the University of Nebraska-Lincoln's Eastern Nebraska Research, Extension, and Education Center (UNL-ENREEC; 380 km southeast of the study site) the morning of the first day of grazing for each treatment. At the end of the grazing season in August, the cattle were returned by truck to UNL-ENREEC. Immediately before being transported to the study site in May, and immediately after being returned to UNL-ENREEC, steers were limit-fed a common hay diet at 1.75% of body weight daily for 5 d in pens at UNL-ENREEC (Greenquist et al. 2009). The steers were weighed on each of the final 3 d of the feeding period. This procedure was followed to minimize the impact of variation in gut fill. We measured animal performance annually from 2011 through 2017.

Data analysis

We examined the effect of grazing treatments on plant community composition over time through permutational multivariate analysis of variance (PERMANOVA) analysis. We chose Bray-Curtis distance because it is not affected by the high number of null values, a common feature in plant community datasets.

We analyzed the data using linear mixed-effect models. We opted for this analysis because it considers the temporal correlation of plant composition and production, utilization, and animal performance data, which were resampled in time within pastures. The fixed-effects parameters were block, treatment, year, and year x treatment interaction. The random effects parameters were block x treatment and block x year interactions. To determine the overall importance of the fixed-effect parameters, we applied the F test with Kenward-Roger statistic in the car package (Fox and Weisberg 2018). For forage quality we included clipping period as a fixed effect and clipping period x treatment, clipping period x year, and block x clipping period x treatment interactions as random effect parameters. We performed visual inspections of residual plots to examine for deviation from homoscedasticity or normality, and we applied square root transformation, when necessary. We used R 4.0.2—loaded with the packages *car*, *dplyr*, *ggplot2, lme4*, *lmerTest*, *multcomp*, *tidyr, vegan*—for data preparation, analysis, and graphic visualization.

Results

Vegetation patterns

Eighty-two plant species were identified on the basis of the step-point method across all years and treatment pastures (Table S1, available online at …). The eight most abundant species represented about 77% of all step-point records and were redtop bentgrass (*Agrostis stolonifera* L.), sedges, common spikerush (*Eleocharis palustris* [L.] Roem. & Schult.), quackgrass, timothy, Kentucky bluegrass, and red and white clover. Changes in the plant community were mainly driven by year effect ($F = 11.193$, $R^2 = 0.609$, $P < 0.001$) with a much lower influence of treatment effect ($F = 4.688$, $R^2 = 0.064$, $P < 0.001$; Table S2, available online at …).

Plant composition

Ground cover measured as litter ($F = 2.062$, $P = 0.0792$), bare ground ($F = 7.945$, $P < 0.001$), and plant base ($F = 2.798$, $P = 0.0236$) was affected by a treatment x year interaction (Fig. 2**;** Table S3, available online at …). Litter cover was consistently above 90% for all three treatments throughout the course of the study, although slightly higher in a dry yr (2012). Bare ground and plant base were consistently below 10% for all three treatments throughout the course of the study.

Treatment effect was significant only for the frequency of occurrence of one of the eight most common plant species. Frequency of occurrence of redtop bentgrass was affected by treatment ($F = 13.089$, $P < 0.001$) and treatment x year interaction ($F = 10.554$, $P < 0.001$) with its frequency being greatest in the mob pastures in 2012 (the drought yr) and not different from the 4PR1 and 4PR2 pastures in all other years (Fig. 3). The year effect was significant for all other species (Fig. S1 and Table S4, available online at …). Frequency of occurrence of sedges ($F = 5.735$, $P = 0.01$), timothy ($F = 2.976$, $P = 0.022$), and common spikerush ($F = 16.234$, $P < 0.001$) was greatest during yr 2011–2014, whereas the grazing-tolerant quackgrass ($F = 11.350$, $P < 0.001$), Kentucky bluegrass ($F = 8.070$, $P < 0.001$), and red ($F = 4.090$, $P = 0.003$) and white clover ($F = 1.972$, $P = 0.095$) were most common during the last 4 yr (2015–2018).

Life forms were more responsive to treatment effect when compared with species-level analysis. Erect forbs were responsive to treatment ($F = 2.770$, $P = 0.089$) and year effects ($F = 12.830$, $P <$

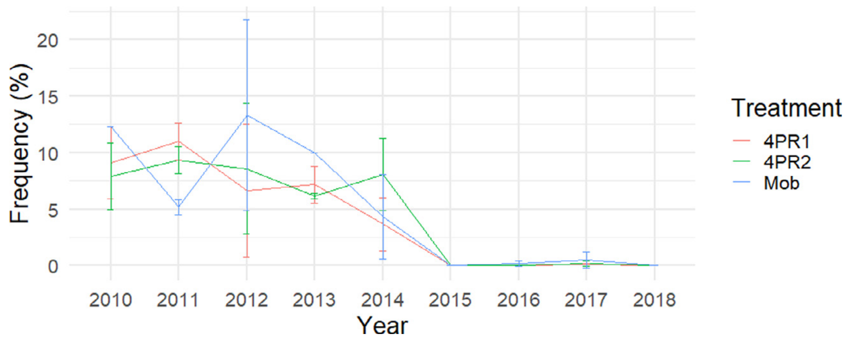

Fig. 3. Relative frequency of redtop bentgrass *(Agrostis stolonifera)* over the 8 yr of the study and three rotational grazing systems (mob: ultrahigh stocking density, 4PR1: four-pasture rotation with one grazing cycle, 4PR2: four-pasture rotation with two grazing cycles) in the Nebraska Sandhills meadows. The remaining species are shown in Figure S1, available online at ...

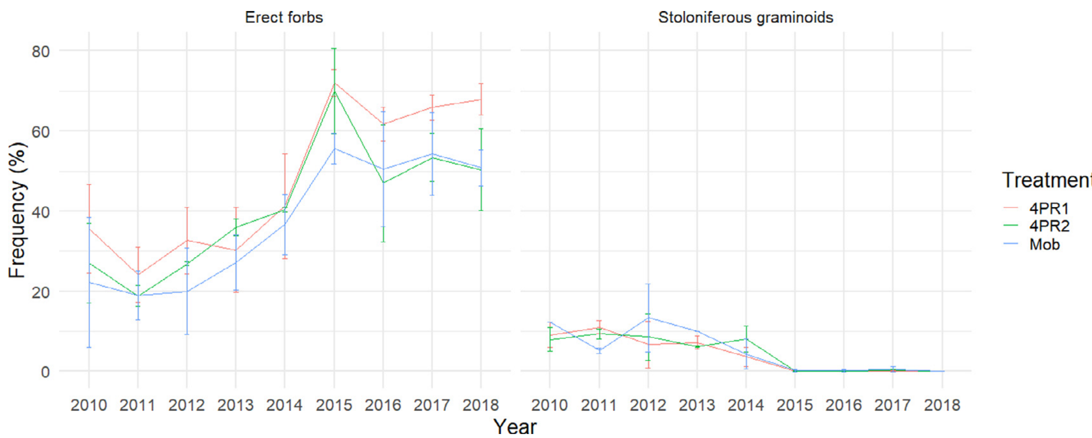

Fig. 4. Relative frequency of occurrence of erect forbs and stoloniferous graminoids over the 8 yr of study and three rotational grazing systems (mob: 120-pasture rotation with one grazing cycle, 4PR1: 4-pasture rotation with one grazing cycle, 4PR2: 4-pasture rotation with two grazing cycles) in the Nebraska Sandhills meadows. The remaining species are shown in Figure S2, available online at ....

0.001), increasing in frequency by 30% over the 8 yr of study, apparently driven by an increase in precipitation after the severe drought in 2012. Stoloniferous graminoids responded to a treatment x year interaction ($F = 10.454$, $P < 0.001$). Frequency of occurrence declined from 10% to around 0% over the study period. These two life forms under the 4PR1 and 4PR2 grazing treatment seem to respond more suddenly to changes in precipitation, while the transition in these two life forms from dry to wet periods was more gradual in the mob grazing treatment (Fig. 4). Rhizomatous graminoids ($F = 9.336$, $P < 0.001$), bunchgrass graminoids ($F = 3.664$, $P = 0.006$), and bush forbs ($F = 5.554$, $P < 0.001$) were only responsive to year effect. Over the study period, rhizomatous graminoids and bunchgrasses showed a reduction in frequency of occurrence of about 20% and 5%, respectively. Bush forbs, on the other hand, had a bell curve frequency of occurrence distribution, showing an increased frequency in the dry period and a frequency reduction in the wetter periods. Rosette forbs, vine forbs, and decumbent forbs did not change in response to any of the factors analyzed (Fig. S2 and Table S5, available online at ...).

The proportion of cool-season ($F = 2.432$, $P = 0.0425$) and warm-season grasses ($F = 2.432$, $P = 0.042$) was affected by treatment x year, which was evident by the increase in the frequency of warm-season grasses in drier years (Fig. 5). 4PR1 differed from 4PR2 and mob treatments in that it showed a more substantial increase in the frequency of cool-season grasses during wetter yr (2015–2018).

The frequency of occurrence of native and exotic species did not vary in response to grazing treatments; however, it did vary in response to year (Fig. S3 and Table S6, available online at ...). We observed an increase in native species frequency in wet years ($F = 4.537$, $P = 0.004$), whereas exotic species ($F = 4.764$, $P = 0.003$) increased in frequency of occurrence in dry years. The proportion of perennial versus annual species was not affected by any of the factors evaluated (Fig. S4, available online at ...).

Aboveground plant production, root growth, and forage allowance

Annual net root growth did not differ between mob grazing and 4PR1 treatments or between the 2 yr (2013 and 2014) root growth was estimated (on average 420 g m^{-2}) (Fig. S6, available online at ...). Aboveground standing live, standing dead, and litter mass in mid-August did not differ by grazing treatment (see Fig. S5; Table S7, available online at ...). Standing live biomass was on average 15% higher in 2018 when compared with the initial year, while litter reduced on average 15% and standing dead biomass showed a small range of values (−2% to 1%) in the same period. Because aboveground plant production and stocking rate did not differ among treatments, cumulative forage allowance (kg dry matter [DM]/AUM) did not differ among treatments. Cumulative forage allowance averaged about 600 kg DM AUM^{-1} over the 8 yr of the study. In similar proportion to stocking density, instantaneous forage allowance (kg DM/AU) at the time of turn-in to a pasture was 30–40 × greater for the 4PR1 and 4PR2 treatments than the mob treatment at different points during the grazing season, again because aboveground plant produc-

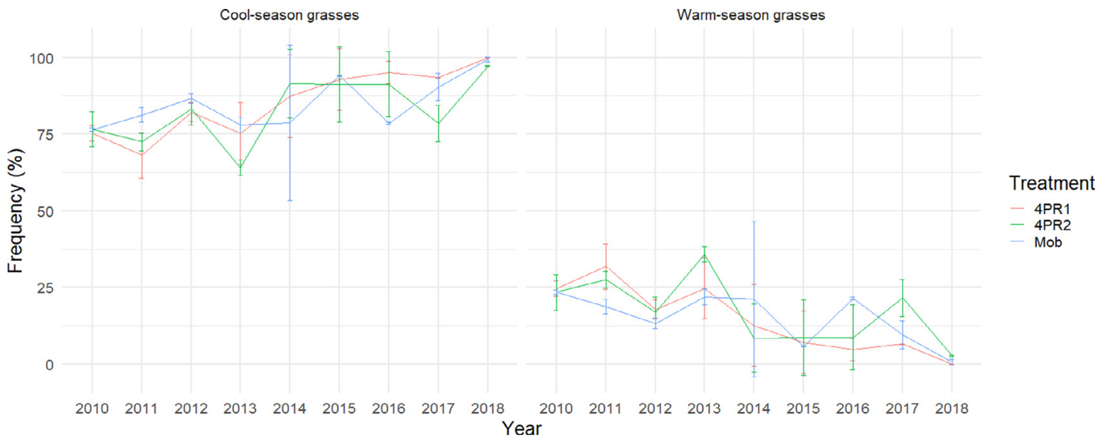

Fig. 5. Relative frequency of occurrence of cool- and warm-season grasses in response to treatment (mob: ultrahigh stocking density, 4PR1: four-pasture rotation with one grazing cycle, 4PR2: four-pasture rotation with two grazing cycles) and yr in the Nebraska Sandhills meadows.

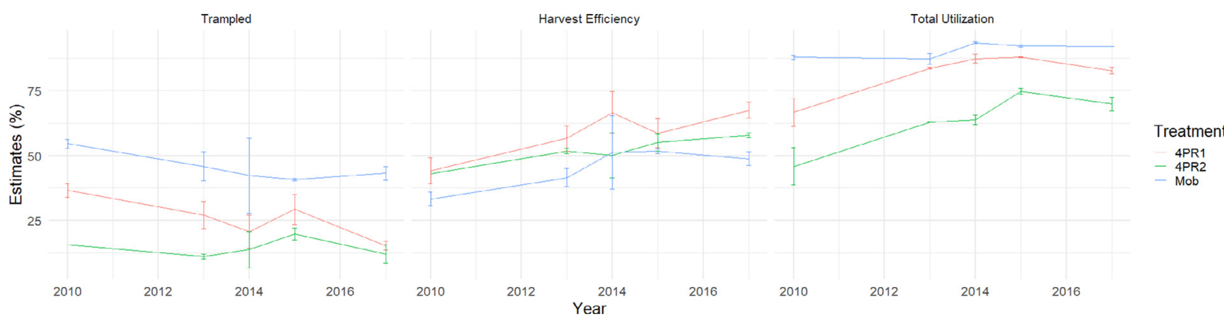

Fig. 6. Percentage trampled, harvest efficiency, and utilization by treatment over the 8 yr of the study in the Nebraska Sandhills meadows. Treatments: mob: 120-pasture rotation with one grazing cycle, 4PR1: 4-pasture rotation with one grazing cycle, 4PR2: 4-pasture rotation with two grazing cycles.

tion and stocking rate did not differ among treatments. Instantaneous forage allowance was as low as 6 kg DM AU^{-1} for the mob treatment in June and as high as 250 kg DM AU^{-1} for 4PR1 in August.

Percentage trampled and harvest efficiency

Percentage trampled was greater in the mob pastures (45.4%) than the 4PR1 (25.9%) and 4PR2 (14.5%) pastures, and percentage trampled did not differ between 4PR1 and 4PR2 treatments (Fig. 6; Table S8, available online at …). Percentage trampled on the mob pastures varied over the 8 yr of study and ranged from 40% to 55% (or 1 632–2 186 kg ha^{-1}), whereas 4PR1 varied from 15% to 36% (or 383–900 kg ha^{-1}) and 4PR2 ranged from 11% to 20% (or 186–329 kg ha^{-1}) for the same 8 yr. The first yr (2010–2013) of the experiment had the greatest percentage trampled in the 4PR1 and mob treatments (F = 33.491, $P < 0.001$) (see Fig. 6). Harvest efficiency responded to treatment (F = 6.108, $P = 0.020$) and year effects (F = 6.532, $P = 0.018$) (see Fig. 6). Over the 8 yr of the study, harvest efficiency was greater for 4PR1 (58.8%) than mob (45.3%), and 4PR2 (51.6%) did not differ from either mob or 4PR1. There was a treatment x year interaction for utilization (F = 17.012, $P < 0.001$; percentage trampling + harvest efficiency), with utilization being lower in 4PR2 pastures than in mob and 4PR1 pastures in all years except in 2015, when it differed from only the mob treatment. Overall, utilization was 90.7% for mob, 81.9% for 4PR1, and 63.8% for 4PR2 pastures.

Forage quality and livestock performance

Crude protein content of aboveground plant biomass only varied in response to a treatment x year interaction (F = 2.180, $P = 0.056$) (Fig. 7). By the end of our 8-yr experiment, the percentage of CP was on average 2.2 percentage units greater in 4PR2 pastures than in 4PR1 or mob pastures. This difference among treatments was more evident in wetter years than in drier years. Although the CP variation within the grazing season was not significant, probably due to the large data variance, CP on the 4PR2 pastures remained constant over the grazing season in the 4 yr that CP was estimated (2010, 2011, 2013, and 2017), whereas CP in the 4PR1 and mob pastures tended to decline over the grazing season in 2 of the 4 yr (2013 and 2017). Animal gain varied in response to a treatment x year interaction (F = 2.180, $P = 0.056$) (Fig. 8). Average daily gain of steers in the 4PR2 pastures was greater than steers in the mob pastures in all years and greater than steers in the 4PR1 pastures in all years except for 2014. Steer weight gains did not differ between 4PR1 and mob pastures in most years. Steers in 4PR1 and mob pastures showed a greater reduction in animal gain in 2015 than for the 4PR2 treatment (Tables S9-S10, available online at …).

Discussion

Mob grazing, as well as other grazing methods, have site-specific management objectives at the time of implementation. This study was designed to test the central hypothesis that mob grazing, when used to maximize trampling of standing vegetation (i.e., minimizing the amount of standing vegetation following a grazing period) results in increased productivity of a diversity of plant species over time (Peterson et al. 2013; Bailey et al. 2019). The increased productivity is reportedly a result of changes in carbon cycle-feedbacks because of increased trampled vegetation, accelerated plant decay, and increased soil carbon content (Peterson et al. 2013). We tested this hypothesis on a Sandhills meadow

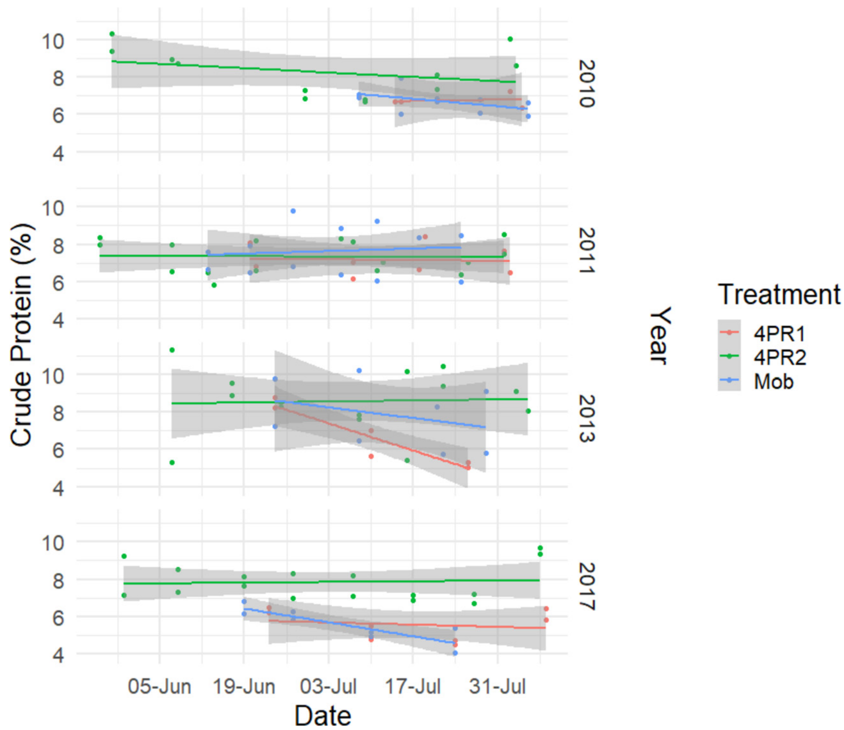

Fig. 7. Crude protein (CP) content of standing plant biomass in 4 of the 8 yr of the study in the Nebraska Sandhills meadows. Treatments: mob: 120-pasture rotation with one grazing cycle, 4PR1: 4-pasture rotation with one grazing cycle, 4PR2: 4-pasture rotation with two grazing cycles.

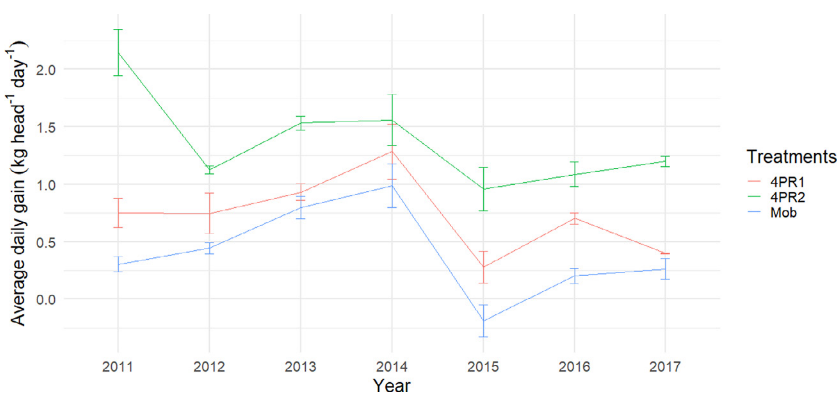

Fig. 8. Average daily gain (kg head^{-1} d^{-1}) of grazing steers from 2011 to 2017 in the Nebraska Sandhills meadows. Treatments: mob: 120-pasture rotation with one grazing cycle, 4PR1: 4-pasture rotation with one grazing cycle, 4PR2: 4-pasture rotation with two grazing cycles.

dominated by cool-season grasses. We opted to start the grazing season for the mob grazing treatment in mid-June, when cool-season grasses were in the elongation and reproductive stages to maximize trampling. The purpose of this study was to determine if 8 consecutive yr of mob grazing with ultrahigh stocking density and associated high trampling affected plant species composition, plant production, and forage quality. We used the same stocking rate on each of the grazing treatments to avoid its confounding effect with stocking density, a recurrent problem in rangeland grazing studies (Scarnecchia 1988).

In our study, plant species composition, aboveground plant production, and root growth did not differ among the treatments. Year and the year x treatment interaction explained most of the variation in our data, which was likely a result of interannual variation in environmental conditions. Numerous studies in arid and semi-arid ecosystems report that vegetation cover is more responsive to climate variability than grazing management intervention (Matches 1992; Booker et al. 2013; Herrero-Jáuregui and Oesterheld, 2018). Recent studies comparing mob grazing and other grazing strategies, primarily continuous stocking, have reported few or no differences in frequency of occurrence of plants, species composition, and aboveground plant production (Tracy and Bauer 2019; Billman et al. 2020). Unlike our study, these studies were short term (2−4 yr) with relatively low stocking densities ($<$ 50 000 kg liveweight ha^{-1}) and percentage trampling was not quantified. Our study is the first to report on a longer-term study at an ultrahigh stocking density ($>$ 200 000 kg liveweight ha^{-1}; Peterson et al. 2013).

The claim that mob grazing would have a greater amount of litter and less standing dead mass (Peterson et al. 2013) did not hold true. Because of increased trampling, litter was expected to be greater in mob pastures. However, no differences among grazing treatments were observed. Guretzky et al. (2020), at the same study site in 2014 and 2015, tested the hypothesis that ultrahigh stocking densities enhance annual litter deposition and, in turn, soil organic matter formation in grasslands. By monitoring litter deposition through the year, Guretzky et al. (2020) reported that annual litter accumulation did not differ between stocking densities. Over a year, accumulated litter in ultrahigh stocking density pastures was largely realized via trampling, whereas accumulated litter in low stocking density pastures was realized via senescence and fall of standing plant tissue. Although we did not monitor temporal dynamics in amount of litter through a year, Guretzky et al. (2020) suggest that aboveground plant mass in a Sandhills subirrigated meadow grassland finds its way to the soil surface regardless of whether it is trampled or not. Other reports of trampling impacts on plant composition and production have been based on simulated trampling and at relatively low stocking densities (Rodriguez et al. 2003; Lezama and Paruelo 2016). These studies propose that trampling increases species richness because of spatial patchiness of disturbance caused by trampling. At the ultrahigh stocking density in our mob treatment, nearly all standing vegetation was either consumed or trampled evenly over the pastures.

As expected, utilization (including trampling) was the greatest in the mob pastures, apparently because of the ultrahigh stocking density. Other studies (Gurda et al. 2014; Reed et al. 2019) involving management-intensive grazing report similar high levels of utilization (79−90%). We designed the mob grazing treatment in this study to maximize trampling, not harvest efficiency; therefore, harvest efficiency for the mob treatment was comparable or lower than that of the 4PR1 and 4PR2 treatments. The cool-season grasses were in the elongation and reproductive stages when grazing was initiated in the mob treatment; therefore, much of the standing vegetation was stemmy (low leaf to stem), largely unpalatable, and more susceptible to trampling. If we would have initiated mob grazing earlier in the season, we likely would have had higher leaf-to-stem ratios, less trampling, and greater consumption (intake). We propose that mob grazing can be designed to optimize harvest efficiency. However, based on nonreplicated, on-ranch data collected on subirrigated meadows of two area Sandhills ranches, Wingeyer (2014) reported harvest efficiencies at 40−45% on mob pastures with initiation of the grazing season in mid to late May. Percentage trampling from 45% to 50% was comparable with our study results. Smart et al. (2010) reported that harvest efficiency increased with increasing grazing pressure; however, the grazing pressures in their analysis did not include the grazing pressures achieved with the ultrahigh stocking densities of our study. Although our study was not designed to determine the effect of a range of grazing pressure and stocking density on harvest efficiency, our results suggest that stocking density is critical in affecting harvest efficiency.

We did not expect forage quality of standing live vegetation in mob pastures to be greater than that of 4PR pastures, especially in the last half of the grazing season when cattle in mob pastures were moved into pastures that had not been grazed previously and were dominated by cool-season grasses in the elongation and mature stages. Crude protein content in 4PR2 pastures was relatively high throughout the grazing season, likely because of the high concentration of vegetative tillers in the 4PR2 pastures compared with the 4PR1 or mob pastures throughout the grazing season. Not only did the grazing season start 20 d earlier for the 4PR2 pastures when grass tillers were mostly vegetative but, because of early-season defoliation in the first cycle, a large portion of tillers in the 4PR2 pastures were vegetative during the second half of the grazing season (field observations). Grass tillers were largely reproductive in the two 4PR1 pastures grazed in the last half of the grazing season. Compared with elongated and reproductive grass tillers, vegetative tillers of perennial grass species commonly found on Sandhills meadows have high CP content and low NDF (Ball et al. 2001). A second grazing period in our study proved to be an important factor in affecting forage quality. The low harvest efficiency (i.e., intake), along with relatively low forage quality of standing live vegetation in the mob pastures, was likely the cause of the low animal gain in the mob pastures. Similarly, Derner et al. (2008) and McCollum et al. (1999) verified that increased grazing pressure in short-duration systems have a negative effect on average daily gain of yearling steers when compared with continuous stocking. Tracy and Bauer (2019) also reported relatively low weight gain for beef cattle on mob pastures.

Implementation of multiple grazing periods during the growing season is reported to impact plant species composition and increase aboveground plant production compared with a single grazing period (Barnes et al. 2008; Norton et al. 2013); however, an 8-yr grazing study on uplands in the Nebraska Sandhills (Stephenson et al. 2015) showed few differences between short duration grazing with three grazing cycles and a simple deferred rotation with a single cycle during the growing season. Low and temporally-variable soil moisture might be the reason for the lack of response of plant composition and production to multiple grazing cycles on upland sites in semiarid regions (Stephenson et al. 2015); however, even with favorable soil moisture conditions on a subirrigated meadow, we did not find a plant composition and production response to number and length of grazing periods. Frequency of occurrence of plant life forms generally did not differ among grazing treatments, but some life forms became more or less common over the years. Some exotic species, such as quackgrass, Kentucky bluegrass, and white and red clovers, tended to increase over the years on all pastures. These species are reported to be grazing resistant (Hendrickson et al. 2020) and respond favorably to open canopies (Ehrenreich and Aikman 1963; Dunn et al. 2016). These species likely increased over time because of the switch from a single annual haying event before initiation of the study to a 60- or 80-d grazing season for 8 yr. As numerous studies (Volesky et al. 2004; Briske et al. 2008; Porensky et al. 2017) have shown, stocking rate and environmental conditions appear to be the critical drivers of plant composition and production.

We hypothesized that there would be a decline in the frequency of occurrence of early-growing, cool-season grasses in 4PR2 pastures over the 8 yr of the study. The favorable soil moisture conditions commonly found on subirrigated sites might be a reason why we did not find a plant composition response to timing of initiating grazing. Also, each pasture in a 4PR2 replication was grazed early only once every 4 yr and in early June or later in 3 out of 4 yr.

The relatively low amount of trampling in the 4PR2 treatment (19%) compared with the 4PR1 (28%) was likely because of differences in spatial distribution of grazing in the last half of the grazing season. In the second cycle, our field observations indicated 4PR2 cattle tended to focus on new vegetative growth in patches that had been grazed in the first cycle, thus avoiding patches that had not been grazed earlier and trampling relatively little standing vegetation. The two 4PR1 pastures grazed in the second half of the grazing season had not been grazed earlier in the season and were characterized by dense stands of stemmy grasses, leading to relatively high amounts of trampling as the cattle moved through the pastures. Others have reported that the long rest periods and low grazing pressures associated with a single grazing period during a grazing season allows plant tissues to mature, decreasing forage quality and animal gain when compared with more frequent grazing intervals (Tracy and Bauer 2019; Vallentine, 2000). Within a forage species, physiological stage of growth at harvest is the most important factor in determining forage quality (Vallentine, 2000; Ball et al. 2001). In general, forage plants in the mob and the 4PR1 pastures were at similar stages of growth at the times of grazing throughout the grazing season.

Management implications

Mob grazing is a rotational grazing technique that is reported to increase carrying capacity of pastures because of increased forage production and/or harvest efficiency. The increased forage production is reported to be realized by maximizing trampling of standing vegetation and incorporation of litter, leading to increased soil C content and soil formation. Relative to conventional four-pasture rotational systems, forage production was not impacted by implementation of mob grazing, even at high trampling percentages of standing vegetation over 8 yr on Sandhills subirrigated meadow. The relatively high levels of trampling were realized by delaying the initiation of the grazing season until mid-June when the dominant cool-season grasses were mostly in the elongation to reproductive stages of growth. Results of this study also demonstrated that the conditions required for high levels of trampling negatively impact harvest efficiency, as well as forage quality and average daily gain of growing beef cattle. We conclude that managing for high levels of trampling through mob grazing cannot be justified because of the resulting decreased harvest efficiency and animal performance/production.

Although further research is needed, greater harvest efficiencies (i.e., > 40%) and associated animal production per unit area likely can be achieved with mob grazing approaches that optimize the timing and frequency of grazing. As mentioned earlier, initiating grazing earlier in the growing season when most grass tillers are in a vegetative stage of growth likely would increase forage quality and harvest efficiency and decrease percentage trampling. Furthermore, implementing two grazing cycles through the grazing season with cattle rotated through all pastures during the first part of the grazing season followed by a second cycle likely would maintain grass tillers in a vegetative stage of growth and increase harvest efficiency. However, the added infrastructure, labor, and management associated with mob grazing may not be justified by an increase in harvest efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2022.02.006.

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