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INFLUENCE OF BURNING AND GRAZING MANAGEMENT PRACTICES ON SUBIRRIGATED SANDHILL MEADOW HAY PRODUCTION

by

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INFLUENCE OF BURNING AND GRAZING MANAGEMENT PRACTICES ON SUBIRRIGATED SANDHILL MEADOW HAY PRODUCTION

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Subirrigated meadows are a valuable forage resource to Sandhills ranching operations being used for hay production, grazing, or a combination of both. Practices that sustain meadow productivity should be encouraged to ensure a consistent feed supply for cattle. The potential influence of prescribed burning or pre-freeze and post-freeze grazing on forage production and quality are not well understood on these meadows. In grasslands, including meadows, excess dead plant material can accumulate, causing a potential reduction in forage yield and quality. Results of our three-year field study suggest that burning meadows in the spring is a suitable management option to remove dead plant material without negatively affecting future hay production. Additionally, when burning was followed by either grazing exclusion or grazing from early-May to early-June, grazing had a greater influence on end of season biomass, with no interacting effect of burning and grazing. Quality of warm-season grasses was increased slightly following burning, but most improvements in quality were minimal and were a result of spring grazing. Study two evaluates a common practice of grazing meadows in the fall (pre-freeze) and winter (post-freeze) months. In our study, grazing in the fall when vegetation was still green was detrimental to future graminoid production. Relative to pre-freeze grazing, postponing grazing until plant dormancy (post-freeze) returned higher yields of graminoids and total live plant biomass. Deterring meadows from grazing in the fall and winter (control) produced graminoid and total live biomass that was similar to post-freeze treatments. Relative to pre-freeze treatments, summer biomass of ungrazed controls were generally higher in graminoid biomass, while similar in total live biomass. Quality of subsequent year’s forage in pre-freeze treatments was significantly higher than the control or post-freeze treatments and met the total digestible nutrient requirement of lactating cows. Our studies show that tradeoffs in quantity and quality are common under any practice. Therefore individual management objectives should be considered when deciding if a practice is right for them.

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CHAPTER 1: LITERATURE REVIEW

The Nebraska Sandhills

The Nebraska Sandhills cover a vast area of west central Nebraska and stretch into the southern edge of South Dakota. The rolling sand dune region is 426.5 kilometers from east to west, and 201.2 kilometers from north to south at their widest point (Bleed and Flowerday, 1990). The area of the Sandhills is approximately 55,000 km^2 (Healey et al. 2011). The Sandhills is one of the largest windblown sand dune regions in the Western Hemisphere and one of the largest grass-stabilized dune regions in the world (Bleed and Flowerday, 1990). The Sandhills are home to approximately 334,244 head of calving cows representing about 20% of the state's cow inventory (Cumming et al. 2019).

The precipitation gradient decreases from east to west across Nebraska, with an average precipitation of 800-850 mm in the southeastern corner to approximately 350-400 mm in the western extreme of the state. The Sandhills receive about 584 mm of precipitation on the eastern border, decreasing to about 432 mm near the western limits. The growing season in the Sandhills spans from April to September, coinciding with 75% of the state's annual precipitation (Wilhite & Hubbard, 1990). The winter season lasts from October through March with snowfall averages of 559-711 mm along the southeastern border and up to 1,143 mm in the North (Wilhite & Hubbard, 1990).

The western edge of the Sandhills experience slightly lower temperatures than the eastern limits. The average temperature for the winter months of October-March is 0°C (Wilhite & Hubbard, 1990). January is generally the coldest month with a temperature range of -6.5 to -4.3°C. July tends to be the hottest month in the Sandhills with daily maximum values of 32.2°C in the southwest, to 31.1°C in the northeast (Wilhite & Hubbard, 1990). In the Sandhills, the freeze-free season (average number of days between the last spring freeze and first fall freeze) is 150 days in the east and 120 days in the northwest (Wilhite & Hubbard, 1990). This pattern is the result of the elevation change in the west of 4,000 feet, which is 2,000 feet higher than eastern elevations (Wilhite & Hubbard, 1990).

Each topographic region in the Sandhills has a varying depth to the water table. The most xeric land type of the Sandhills is upland range, which has a water table depth of about 10 meters from the surface (Healey et al. 2011). Upland range constitutes 65% of the land area of the Sandhills (Healey et al. 2011), making it the most distinctive land cover types of the region. At water table depths of one to ten meters below the surface, dry valleys prevail, covering approximately 20% of the region (Healey et al. 2011). Mesic areas, where the water table is within one meter of the soil surface, are classified as subirrigated meadows (Healey et al. 2011). These meadows cover about 10% of the region (Healey et al. 2011). Some of the water that percolates through sand dunes eventually settles in the High Plains Aquifer (Healey et al. 2011). As this reserves fills, it gives way to lakes and wetlands that cover approximately 5% of the Sandhills land area (Healey et al. 2011).

Studies in the Nebraska Sandhills reveal topography influences plant species distribution of upland range (Barnes and Harrison, 1982; Barnes et al. 1984; Schacht et al. 2000). The major topographic positions of upland range in the Sandhills are interdunes and dune positions. Interdunes are in the lower lying valley regions, while dune positions include north-and-south facing slopes along with dune tops. Studies of

Sandhills vegetation distribution reveal that shallow rooted species often dominate interdune positions (Barnes and Harrison, 1982; Barnes et al. 1984; Schacht et al. 2000). Common cool-season species found in interdunes include western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Love], needle grasses (*Stipa* L. spp), bluegrasses (*Poa* L. spp.) and sedges (*Carex* L. spp.) (Barnes et al. 1984; Schacht et al. 2000). Prevailing warm-season grasses in the interdunes include blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] and switchgrass (*Panicum virgatum* L.) (Barnes et al. 1984; Schacht et al. 2000). Forbs such as white sage (*Artemisia ludoviciana*) and western ragweed (*Ambrosia psilostachya*) along with the shrub, prairie wild rose (*Rosa arkansana*) are also prevalent in interdune regions (Schacht et al. 2000). On north-facing slopes, cool-season grasses are mostly dominant and include needle grasses (*Stipa* L. spp), Junegrass [*Koeleria pyramidata* (Lam.) Beauv.], and Wilcox panicum [*Dichanthelium wilcoxianum* (Vasey) Freckmann], while the warm-season grass little bluestem [*Schizachyrium scoparium* (Michx.)] is also associated with this site (Schacht et al. 2000). South-facing slopes tended to be associated with warm-season grasses such as prairie sandreed [*Calamovilfa longifolia* (Hook) Scribn.] and sand bluestem (*Andropogon hallii* Hack.) (Schacht et al. 2000). In addition, the forbs western ragweed and stiff sunflower (*Helianthus rigidus*), along with the shrubs leadplant (*Amorpha canescens*), prairie wild rose, and yucca (*Yucca glauca*) are also common on slope regions (Barnes et al. 1984; Schacht et al. 2000).

Soil factors influence the distribution of plant species at the varying upland range topographic positons. In the western Sandhills, the soil of dune tops and dune slopes consists of coarse-textured sand while interdunes have finer-textured sandy soils (Barnes and Harrison, 1982; Barnes et al. 1984). In the eastern Sandhills, soils of both dune positions and interdunes contain loamy sand soil (Schacht et al. 2000). However, organic matter content was higher in the interdunes in both regions (Barnes and Harrison, 1982; Schacht et al. 2000). The higher water-holding capacity of organic matter in the subsurface soil likely influenced the greater association of shallow-rooted, cool-season species in the interdunes (Barnes and Harrison 1982, Barnes et al. 1984). The C_3 photosynthetic pathway of cool-season species works most efficiently when adequate soil moisture is available. Total plant production and precipitation use efficiency, a ratio of plant production and precipitation at a given time, was higher in interdune positions relative to dune positions (Stephenson et al. 2019). The high composition of cool-season species in the interdunes is more sensitive to growing season precipitation than the species of the dune positions (Stephenson et al. 2019). Relative to dune positions, plant production is more significantly increased in wet years and decreased in dry years in the interdunes than slope positions (Stephenson et al. 2019).

Subirrigated meadows

Most of the Sandhills rangeland is upland range, but approximately 10% of the total land area consists of subirrigated meadows (Healey et al. 2011). While subirrigated meadows are a relatively small percentage of the Sandhills, they serve as a valuable forage resource to ranchers. Subirrigation of meadow vegetation often leads to a substantial production of forage available for hay production and grazing. In 1991, Coady and Clark (1993) administered a comprehensive survey to 128 Nebraska Sandhills range cattle operations. The respondents indicated that the primary use of subirrigated meadows is for hay production. Respondents reported that most of the hay is harvested in June and July when the meadows typically become dry enough to allow haying to occur. Hay yields on their subirrigated meadows were in the range of 1,121 – 6,725 kg·ha^{-1} with an adjusted mean of 3,138 kg·ha^{-1}. Fertilizer use on meadows was not surveyed. Yields from an unfertilized meadow study at the Gudmundsen Sandhills Laboratory (GSL) in the Nebraska Sandhills were 3,870 kg·ha^{-1} in mid-June and 6,090 kg·ha^{-1} in mid-August (Reece et al. 1994).

Nichols et al. (1990) reports that low soil fertility is often the cause for low forage yields on some meadows. In efforts to increase meadow productivity, Nichols et al. (1990) applied nitrogen (N), phosphorous (P) and sulfur (S) to meadows in the spring to realize the additive effects on yield resulting from this combination. When averaged over P and S applications, each 45 kg·ha^{-1} incremental increase in N from 0 to 135 kg·ha^{-1} resulted in dry matter yields increasing by 1,002, 703, and 402 kg·ha^{-1}, respectively. In this study, the highest yields were achieved when N, P, and S was used at rates of 135, 20, and 22 kg·ha^{-1}, respectively. This fertilizer combination increased the four-year annual yield by 3,716 kg·ha^{-1} compared to no fertilizer. Reece et al. (1994) also saw positive increases in dry matter yield with increasing N levels. With no added N, yields increased by 1,640 kg·ha^{-1} from mid-June to mid-July, however with 135 kg·ha^{-1} N, yields increased by 2,930 kg·ha^{-1} during this same time. However, at some point, the increasing yield from increasing N may not be economically viable. When averaged over P and S, Nichols et al. (1990) found nitrogen use efficiency was highest for N rates of 45 kg·ha^{-1} and lowest under N rates of 135 kg·ha^{-1}. The study also found that the first incremental increase of N from 0 to 45 kg·ha^{-1} decreased crude protein concentration by as much as 9.2 $g \cdot kg^{-1}$. In addition, each 45 $kg \cdot ha^{-1}$ N increase (from 0 to 135 $kg \cdot ha^{-1}$) led to an approximate 9 $g \cdot kg^{-1}$ reduction of in vitro dry matter digestibility (IVDMD).

The distinguishing characteristic of subirrigated meadows is that the water table is within one meter of the surface. The depth to the water table directly influences the vegetation composition of subirrigated meadows. Ehlers et al. (1952) gives the following detailed descriptions of the varying community compositions of wet meadows in response to their distance from the water table. When the water table is at a depth of 0.03 - 0.46 m from the surface, sedges, prairie cordgrass (*Spartina pectinata* Link), Northern reedgrass (*Calamagrostis stricta* (Timm) Koeler ssp. *inexpansa* (A. Gray) C.W. Greene), bluegrass, redtop bent (*Agrostis stolonifera* L.), and reed canarygrass (*Phalaris arundinacea*) are the predominant grasses. Legume species at this depth include alsike clover (*Trifolium hybridum* L.) and white clover (*Trifolium repens* L.). At a depth of 0.46 – 0.76 m sedges, redtop bent, and bluegrass are still present, but the tallgrasses big bluestem (*Andropogon gerardii* Vitman), indiangrass (*Sorghastrum nutans*) and switchgrass emerge. Common legumes at this depth are red clover (*Trifolium pratense* L.), black medic (*Medicago lupulina*), and sweetclover (*Melilotus alba*). At a depth of 0.76 – 1.52 m, tallgrasses are the dominant community being made up of big bluestem, little bluestem, indiangrass, and switchgrass, with black medic and sweetclover present. Finally, at a depth of over 1.5 m, little bluestem, hairy grama (*Bouteloua hirsuta*), blue grama, needlegrass, and prairie sandreed are the prevalent plant community.

Keim et al. (1932) describes similar plant communities in a Nebraska Sandhills meadow, detailing at a water table at 1.20 m below the soil surface that the big bluestem-indiangrass communities dominated. In this same meadow, when the water level was

0.51 m deeper needlegrasses and the grama grasses prevailed. In another meadow with a water depth 0.61 m, Keim et al. (1932) found that reed canarygrass along with perennial smartweed (*Polygonum* spp.) dominated. When water was 2.3 m below the surface, grama grasses made up the entirety of the vegetation.

Volesky et al. (2011) states that on most Nebraska wet meadows native rushes and sedges are dominant along with introduced cool-season grasses and legumes. Timothy (*Phleum pratense* L.), redtop bent and Kentucky bluegrass (*Poa pratensis* L.) make up a vast majority of the introduced grasses in subirrigated meadows (Keim et al. 1932). Meadows are sometimes seeded with legumes to increase forage quality and yield of forage. The ability of legumes to fix nitrogen is an added benefit. Common introduced legumes in Nebraska meadows include red clover, white clover, alsike clover, and sweet clover (Keim et al. 1932)

Meadows in the Sandhills are likely to contain both cool-season and warm-season plant species. Therefore, to effectively utilize meadows, grassland managers must have a general understanding of the varying growth cycles and physiology of the respective species. Cool-season grasses grow best in temperate, wet conditions. The optimal growing temperature for most cool-season grasses falls within the range of 15 to 25°C (Nelson, 1996). Below 10°C, growth rapidly drops off, but slow growth does occur at 5°C (Moser & Hoveland, 1996). In regards to Nebraska, native cool-season perennial grasses typically begin growth in mid- to late-March and reach maturity by late-June. As temperatures rise and moisture becomes limiting, cool-season grasses experience a "summer slump". During this "summer slump," they go into dormancy until cooler and wetter weather returns resuming active growth, usually in September and October.

Interestingly, some cool-season annuals, such as downy brome (*Bromus tectorum* L.), avoid the heat altogether by maturing and producing seed before its onset (Moser & Hoveland, 1996). In contrast, warm-season grasses are best suited for warm, dry climates, with an optimal growth temperature range between 30 to 40°C (Nelson, 1996). In Nebraska, native warm-season grasses often begin growth in early-May and remain actively growing until late-August, before going dormant for the winter.

Inherent physiological differences exist between the photosynthetic pathways of the two functional groups. Cool-season grasses carry out C_3 photosynthesis while warm-season grasses carry out C_4 photosynthesis. In C_3 photosynthesis, atmospheric CO_2 enters the plant and diffuses into mesophyll cells. Once inside, CO_2 enters the Calvin cycle where the enzyme rubisco generates a three-carbon compound known as 3-phosphoglyceric acid (PGA). Next, the product is reduced to produce a three-carbon sugar known as G3P. Some of the G3P goes on to produce glucose or other sugar molecules used in synthesis of plant tissues. The remaining G3P goes on to regenerate rubisco and to start the Calvin cycle again. In most situations, this process dominates but when O_2 becomes increasingly available, rubisco may fix oxygen instead of carbon dioxide. The fixing of oxygen by rubisco is termed photorespiration. Photorespiration results in an overall reduction in the efficiency of photosynthesis. In addition, photorespiration increases in hot, dry weather because the plant closes its stomata to preserve water. Once stomata are closed, CO_2 cannot flow in and O_2 cannot flow out, increasing the O_2 concentration in the cell and the chances rubisco will bind with O_2.

Overtime, the C_3 photosynthetic pathway evolved into a more efficient C_4 photosynthetic pathway. The C_4 pathway likely has tropic origins, adapting in response to hot, arid climate (Waller & Lewis, 1979). In C_4 photosynthesis, CO_2 first enters the stoma and diffuses into the mesophyll cells. CO_2 binds with the phosphoenolpyruvate (PEP) enzyme to create the first product of C_4 photosynthesis, oxaloacetate. Oxaloacetate is then formed into a similar compound, known as malate. Malate diffuses out of the mesophyll cells into adjacent bundle sheath cells. There, it breaks down and produces a CO_2 molecule and a three-carbon pyruvate molecule. The CO_2 molecule proceeds to the Calvin cycle where it is used to initiate C_3 photosynthesis. Meanwhile, the pyruvate molecule diffuses out of the bundle sheath cell into the mesophyll cell, and with the help of ATP, regenerates PEP. This close association of the mesophyll cells with the bundle sheath cells allows rapid re-capture of any CO_2 loss from photorespiration, greatly improving efficiency (Waller & Lewis, 1979). The PEP enzyme also has a higher affinity for CO_2 than rubisco, allowing more CO_2 to become available for photosynthesis in the bundle sheath cells (Ehleringer & Monson, 1993). All of these factors help to make C_4 photosynthesis more efficient. In fact, the greater efficiency of CO_2 fixation by C_4 plants is accredited to a two- to –three- fold increase in dry matter production over C_3 plants (Black, 1971 *in* Waller & Lewis, 1979).

Fire and Grazing Interaction

Often in spring and into early summer, the close proximity of the water table to the surface of subirrigated meadows impedes haying or cattle grazing. As a result, standing dead plant material and excessive litter buildup can occur on some of the wetter areas of the meadows. The dead plant material can potentially retard growth of new vegetation, influence selectivity of grazing cattle, and reduce the quality of hay by increasing the amount of lower quality plant material in the hay bale. One solution to rid the meadow of this dead plant material is with prescribed burning.

The employment of fire in grassland systems is not a novel concept. Lightning strikes, along with ignition by Native Americans, were common causes of fire on the prairie before European settlement (Middleton et al. 2006). Historically, lightning fires on the Northern Great Plains were most common in the months of July and August (Higgins, 1984). However, lightning fires are less common in the modern day because of overgrazing on pastures, landscape fragmentation from cultivation and infrastructure development, and fire suppression by humans (Whitlock et al. 2010; Higgins, 1984). Human suppression of fire is common today because of the risk of loss of property and life. Suppression of fire has enabled the encroachment of woody species on many North American rangelands, resulting in a drastic decline in rangeland ecosystem services such as biodiversity, water recharge, and livestock production (Twidwell et al. 2013). In the Kansas Flint Hills, tallgrass prairies were turned into a closed canopy red cedar (*Juniperus virginiana* L.) forest in as little as 40 years (Briggs et al. 2002). The loss of grazing lands to woody encroachment has worried many private landowners, spurring development and participation in local burn cooperatives throughout the Northern Great Plains (Twidwell et al. 2013). These burn cooperatives utilize and promote the use of prescribed fire to restore grasslands.

The interacting effects of fire and large ungulate grazing (particularly bison), are key attributing factors for creation of North American grasslands (Kerby et al. 2007; Knapp et al. 1999). As fires burned the Great Plains, bison would follow the fires concentrating their grazing in the recently burned areas while neglecting the adjacent unburned areas (Fuhlendorf and Engle, 2004). Bison are attracted to the enhanced palatability of the fresh, green regrowth following fire, spending as much as 70% of their time on these burned areas (Fuhlendorf et al. 2017; Fuhlendorf and Engle, 2004). This "pyric herbivory," created landscape heterogeneity through altering of grassland structure with co-existing grass patches in various stages of recovery from disturbances (Fuhlendorf and Engle, 2001). In the tallgrass prairie of the Northern Great Plains, creating heterogeneity through fire-grazer interactions has been successful when moderate to heavy stocking is employed (Fuhlendorf and Engle, 2004; Fuhlendorf and Engle, 2001). However, in the Nebraska Sandhills, spatial heterogeneity was not achieved in lightly stocked patch burned units (Arterburn et al. 2019). Therefore, the utilization of patch burn grazing to increase heterogeneity may be most successful when grazing demand of livestock challenges forage supply.

Patch burn grazing is a management strategy used to mimic the effects of fire and grazing herbivores on a landscape. As mentioned previously, large ungulates are attracted to the increased palatability of post-fire regrowth. The higher quality and digestibility of recently burned areas has been accredited to increased livestock gains (Limb et al. 2011; Anderson, 1964; Green, 1929). Greene (1929) found that annual burning of bluestem pastures in Mississippi increased cattle gains by 20 $kg \cdot ha^{-1}$, with the greatest weight gains occurring 60-90 days post fire. Similarly, weight gain in cattle was attributed to the increased protein content and digestibility of little bluestem following late spring burning in the Kansas Flint Hills (Anderson, 1964). In mixed-grass pastures in the Southern Great Plains, weight of stocker cattle on patched burned pastures was compared to those on traditionally managed unburned pastures (Limb et al. 2011). By year five of the study, stocker cattle on patch burned pastures gained about 18-22 kg per animal more than stockers on unburned pastures. In addition, supplemental feed requirements were 40% less in the pastures managed with patch burn grazing compared to the traditionally managed pastures (Limb et al. 2011). Therefore, patch burn grazing may be an economically viable management practice for livestock operations given that supplemental feed costs have been attributed to over 60% of annual cow cost (Miller et al, 2001). In some cases, no differences in cattle performance between patch burn and traditionally managed pastures are noted. In the tallgrass prairie of Nebraska, cattle performance on patch burned pastures was compared to that of those on pastures burned entirely at the onset on the study (Winter et al. 2014). When averaged across three study years, body condition scores of cows was similar among both the patch burned and once burned pastures.

The seasonal time of a burn plays a critical role in the management of species composition of the grassland. Burning that coincides with the timing of peak growth of a species has the ability to hinder its growth and allow for a competitive advantage to other species (Howe, 2000). Defoliation events (i.e., mowing, grazing, and fire) reduce the leaf tissue available for photosynthesis, thereby forcing the plant to draw energy from roots, potentially limiting future growth of the plant (Belsky, 1987). In a mesic Wisconsin grassland, two alternate year spring burns favored C_4 species at the expense of C_3 species (Howe, 2000). Also in Wisconsin, Bouressa et al. (2010) applied spring burning to promote persistence of warm-season grasses into a cool-season dominated site. Following three years of prescribed burning, native warm-season grass tiller density and cover increased most significantly in burned only treatments compared to burned-grazed and grazed only treatments (Bouressa et al. 2010). In contrast, following two years of late growing season burning, production of cool-season perennial grasses increased in a mid-successional tallgrass prairie in Oklahoma (Engle et al. 1998). In addition, late season burning favored forbs, with forb production increasing more substantially following two and three years of successive burning (Engle et al. 1998).

The location of a growing point of a grass can also dictate its response to fire. Rhizomatous grasses are generally more resilient to fire than bunchgrasses (Ewing and Engle, 1988). Soil protects below ground buds of rhizomatous grasses from the direct effects of heat. Tillers of bunchgrasses initiate growth from meristems located on the base of the crown and elongate as the growing season progresses, making them susceptible to heat damage from fire (Ewing and Engle, 1988). The accumulation of dead tillers in the crown of bunchgrasses also provides high fuel loads for fire. This fuel load has the potential for increased fuel dosage and heat duration, resulting in meristematic tissue damage of the plant (Engle et al.1998; Wright 1971). In the Nebraska Sandhills, fire can be especially damaging to the productivity of the bunchgrass little bluestem (Volesky and Connot, 2000; Pfeiffer and Steuter, 1994). Furthermore, increased palatability of regrowth and removal of old growth makes little bluestem susceptible to heavy grazing pressure following fire (Pfeiffer and Steuter, 1994). Fire can also be damaging to the bunchgrass needle and thread (*Hesperostipa comata*). Following three years of fire in the northern mixed-grass prairie of Montana, burned plots had 73% less needle and thread buds than unburned plots (Russell et al. 2015). In some instances, fire can be used as a tool to control invasive bunchgrass species. In the Northern Great Plains, fire has shown potential to reduce purple threeawn (*Aristida purpurea*), an invading species capable of forming monocultures and reducing plant diversity (Russell et al. 2013).

Litter

In areas of fire suppression, excess dead plant biomass begins to accumulate in the plant canopy (standing dead) and on the ground (litter). Decades of absence of fire and grazing resulted in monocultures of big bluestem in Kansas with associated litter accumulation averaging 40 cm (Hulbert, 1969). A similar monoculture of big bluestem also developed on a prairie in Nebraska that had been abandoned for over 15 years with litter accumulation of 13.97 to 17.78 cm (Weaver and Rowland, 1952). Excessive buildup of dead plant material can negatively affect future plant growth and production.

Litter's shading effect on the soil surface can result in lower soil temperatures (Ewing and Engle, 1988; Knapp, 1984; Weaver and Rowland, 1952). Lower soil temperatures experienced under litter and standing dead plant material can delay spring growth and can lead to later reductions in production (Knapp and Seastedt, 1986; Hulbert, 1969). In big bluestem stands, soil temperatures of control plots with heavy litter (15,692 $kg \cdot ha^{-1}$) were 1° to 5°C lower throughout the growing season compared to average temperatures of denuded (burned or clipped) plots (Hulbert, 1969). In this study, soil temperatures were taken in the first 10 to 20 cm of the soil profile. By the end of the growing season, production of denuded plots was 1.8 times greater than control plots (Hulbert, 1969). In another study of big bluestem prairie, emerging shoots in unburned prairie experienced 58% less photosynthetically active radiation (PAR) than those of burned prairie (Knapp, 1984). This reduction in PAR occurred during the first 30 days of the growing season and resulted in a 55.4% reduction in production during this period compared to unburned prairie (Knapp, 1984).

The shaded environment under litter may also lead plants to develop “shade characteristics” (Knapp and Seastedt, 1986). These characteristics include leaves and stems of big bluestem becoming thinner than those of burned prairie resulting in reductions in grass production (Hulbert, 1969; Weaver and Rowland, 1952). Additionally, early in the growing season leaves of big bluestem in undisturbed (low irradiance) prairies had lower stomatal density, pore length and conductance than those of burned (high irradiance) prairie (Knapp and Gilliam, 1985). In an attempt to “escape” dark environments and enter into areas of higher irradiance, plants increase the rate of internode elongation (Ballaré et al. 1991). In switchgrass stands in Nebraska, tiller height of control plots in late-June was 10 to 20 cm taller than tillers in treatments where litter was removed (Schacht et al. 1998).

Despite its negative effects to plants, litter can also positively alter the plant environment. Increases in aboveground cover, either living or dead, in an ecosystem increases soil infiltration and reduces sediment erosion loss (Thurow et al. 1986). In the Edwards Plateau of Texas, bunchgrasses were more effective than sodgrasses in obstructing overland sediment transport and protecting the soil from the impacting force of raindrops (Thurow et al. 1986). Relative to sodgrasses, bunchgrasses have more total aboveground biomass and organic matter production making them more effective at protecting the soil (Thurow et al. 1986). Litter’s ability to lower the soil temperature also results in a reduction in evaporation, ultimately conserving soil moisture. The litter canopy reduces evaporation by creating a vapor barrier where relative humidity is maintained (Facelli and Pickett, 1991). Studies of native prairies found that soil moisture was greater in areas with litter relative to those that had been defoliated (Duetsch et al. 2010; Hulbert, 1969). In native and tame grasslands in a dry sub-humid region of Canada, high litter levels (5,500-14,000 $kg \cdot ha^{-1}$) helped to conserve soil moisture during the growing season (Duetsch et al. 2010). Litter was attributed to maintaining soil moisture levels or reducing total moisture loss after rainfall (Duetsch et al. 2010). In this study, high litter levels improved or stabilized production. In contrast, in a high rainfall year in the tallgrass prairie of Nebraska, only minor differences in soil moisture were found between heavy litter and defoliated plots (Weaver and Rowland, 1952). In a meta-analysis of the effects of litter on vegetation, Xiong & Nilsson (1999) found that the general trend in deserts is that litter has a positive impact on plant establishment and a negative effect in all other ecosystems. In dry environments, maintaining adequate litter levels may be a critical factor in maintaining plant productivity, but in more humid or wet environments excess litter may have some negative consequences.

Prescribed burning has been an effective tool for removing dead plant material and increasing forage quality in many grassland ecosystems. As is the case in other grasslands, excessive dead plant material may limit forage production and reduce forage quality on subirrigated meadows. Yet, no research currently exists that investigates the effectiveness of prescribed burning on subirrigated meadows in the Nebraska Sandhills. It is our goal to narrow this knowledge gap. Chapter 2 of this thesis will examine the influence of spring burning on Sandhills subirrigated meadow environments on forage production and quality later in the growing season.

Fall and winter grazing of subirrigated meadows

The variability in growth cycles of warm- and cool-season grasses allows for a greater heterogeneity of forage available throughout the year. Grazing of upland range in the Nebraska Sandhills is often limited to a grazing season from mid-May to mid-October. Thereafter, extending the grazing season through use of plant regrowth following haying on subirrigated meadows is a common practice. In the early 1990s, approximately 80% of ranchers with subirrigated meadows reported using them for grazing (Coady and Clark, 1993). Grazing of hay regrowth is a management practice in the region employed by more than half of cow/calf operations with meadows (Coady and Clark, 1993). Grazing of hay regrowth commonly begins in October and lasts for about a month, while winter grazing of meadows is equally practiced and typically begins in November and lasts until March (Coady and Clark, 1993).

Grazing meadows during the dormant season provides financially beneficial options to ranchers because it reduces hay-feeding costs (Volesky et al. 2002; Adams et al. 1994). Adams et al. (1994) found that grazing meadows in May, and again during the dormant season, resulted in the greatest economic returns to operations compared to systems that fed hay in the winter. In a different approach, Volesky et al. (2002) found that allowing weaned steer calves to graze hay windrows on a Sandhills subirrigated meadow during the winter months improved economic returns over a traditional bale hay feeding system. Systems that rely more on cattle grazing rather than machines to harvest forage is one method to reduce an operation’s feed cost (D’Souza et al. 1990). Extending the grazing season with meadows is economically justified but given limited availability of meadows on some operations, it is not always possible.

The effects of fall and winter grazing on the subsequent year's production is less clear on subirrigated meadows. Ample research of the effects of dormant season grazing on the subsequent year's herbage production exists for upland grassland systems (such as semi-arid uplands). Knowledge in these studies can be used in trying to understand the effects of dormant season grazing on meadow productivity. In the Kansas Flint Hills, intensive early stocking of pastures from May 1 to July 15, followed by grazing during the dormant season, did not reduced production of big bluestem the following growing season (Auen and Owensby, 1988). When given sufficient recovery time after grazing, translocation of total non-structural carbohydrates to wintering storage organs of big bluestem occurred by early September (Owensby et al. 1977). In the semi-arid Dakotas, summer flash grazing at 25% utilization followed by 50% utilization of forage in the winter did not negatively affect herbage production the following growing season (Nelson et al. 2006). On Sandhills uplands, light defoliation in the summer followed by mid-October grazing at either 0, 1, 2, or 3 AUM ha^{-1} on either warm-season and cool-season dominated sites was studied (Mousel et al. 2011). Regardless of October stocking rate, herbage production was not impacted the following growing season on warm-season dominated sites. However, on cool-season dominated sites in the study, increases in October stocking rate led to associated decreases in herbage production the following growing season. In Wisconsin, Riesterer et al. (2000) studied October, December, and March defoliation of cool-season grass species and its effect on the following growing season's production. Results indicate that defoliation during October or December did not affect total production the following growing season. However, when spring growth occurred before grazing in March, spring forage production was reduced the following growing season.

In summary, fall and winter grazing of subirrigated meadows is an economical way for Sandhills production systems to extend the grazing season. Grazing during winter months reduces the amount of hay fed improving net returns to producers. In regards to its impact on range health, the results suggest that a site's response to dormant season grazing depends on the dominant plant community present. Warm-season dominated sites that are grazed during the dormant season generally see no reductions in yield the following growing season. However, since cool-season grasses can grow at temperatures as low as 5°C, caution should be used on cool-season dominated sites when grazing occurs before dormancy of the species. Allowing cattle to graze before the onset of a hard frost could deplete plants' carbohydrate reserves, which are used to initiate growth the following spring. In turn, this may lower biomass production and reduce forage available for haying and/or grazing during the subsequent growing season. Chapter 3 of this thesis will further look into the effects of fall and winter grazing on a cool-season dominated Sandhill subirrigated meadow at heavy and moderate intensities.

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CHAPTER 2: EFFECT OF EARLY-SEASON BURNING AND GRAZING ON SUBIRRIGATED MEADOW FORAGE PRODUCTION AND QUALITY

Introduction

To continue to benefit from the numerous ecosystem services that rangelands provide, we must ensure their sustainability. Rangelands provide a host of services including carbon sequestration, wildlife habitat, recreational opportunities, and the provisioning of fiber and food (Briske, 2017). However, the provisioning service of food production continues to be the primary ecosystem service of rangelands (Yahdjian et al. 2015). By 2050, it is expected that the population will rise to 9.3 billion and the need for food from our rangelands will become even more critical (FAO, 2014).

Native rangelands are crucial to support the livelihoods of those who raise livestock for protein consumption. The Nebraska Sandhills, for example, support more than half a million head of cattle and bolster the state's main industry; beef production (Arterburn et al. 2019). Cattle ranching is possible in the Sandhills because of the co-existence of two unique landforms; upland range and subirrigated meadows. Upland range, accounts for a majority of the Sandhills land area and is used as a main source of grazing during the summer months (Healey et al. 2011; Mousel et al. 2011). Subirrigated meadows make up only about 10% of the Sandhills' area, but are critical for hay production and extending the grazing season into the fall and winter months (Healey et al. 2011; Mousel et al. 2011).

Subirrigated meadows, while small in land area, have immense value to Sandhills ranchers. The water table is typically within one meter of the soil surface during the growing season for most subirrigated meadows (Healey et al. 2011). Constant access to water during the growing season results in high forage production on meadows. Clipping estimates at the Gudmundsen Sandhills Laboratory in the north central Sandhills, show that forage production of subirrigated meadows is two to three times greater than production of associated uplands. Meadows are typically used for hay production, but grazing or a combination of both haying and grazing regrowth are also important for some operations (Coady and Clark, 1993). In the summer, hay harvested from the meadows is often the primary feed source for livestock during the winter and spring months (Coady and Clark, 1993).

One issue that influences productivity and hay quality of Sandhills meadows is the buildup of dead plant material. In some years, high water tables can prevent haying of some of the lower lying areas of the meadows. Additionally, heterogeneous grazing patterns (i.e., areas of heavy grazing intermixed with areas of little to no grazing) by cattle can result in areas with a substantial buildup of dead plant biomass. Accumulation of dead plant material in rangelands can reduce forage quality, delay spring growth, reduce tiller density, intercept rainfall, and potentially lower forage production (Kerby et al. 2007; Knapp and Seastedt, 1986; Hulbert, 1969; Weaver and Rowland, 1952; Dysksterhuis & Schmutz, 1947; Knapp 1984).

Management practices such as prescribed burning and mowing are effective at removing dead plant material from rangelands (Vermeire et al. 2020; Dickson, 2019; Schacht et al. 1998). Prescribed burning also has the added benefit of returning nutrients to the soil (Knapp & Seastedt, 1986; Frost & Robertson, 1987). The degree to which mowing affects plant production is often influenced by the frequency of mowing, whereby production decreases with annual mowing, but is not affected with biennial mowing (Zhao et al. 2020). While effective at removing dead biomass, annual burning can reduce species diversity and alter species composition (Valko et al. 2018; Kahmen et al. 2002; Moog et al. 2002). Researchers reported no difference in total annual production between burning or mowing on upland mixed prairie (Vermeire et al. 2020) and tall grass prairie (Schacht et al. 1998), but less research is available that has evaluated these practices on subirrigated meadows managed for cattle grazing and hay production.

Most of the available research has focused on the effects of burning or mowing on upland rangeland areas. However, less research is available that has evaluated the effects of these management practices in mesic rangelands like subirrigated meadows. Given the importance of subirrigated meadows to ranching operations, the effects of early-season burning and mowing as vegetation management tools were evaluated. Additionally, a potentially interacting variable of early-season grazing following fire on meadow vegetation was investigated. The objectives of this study were to 1) evaluate the effectiveness of spring burning or mowing in removing dead plant material from meadows, 2) determine the effects of spring burning and mowing on end of season forage production and forage quality, and 3) investigate the potentially interacting effect of grazing following the burn on vegetation characteristics. We hypothesized that spring burning would remove standing dead and litter on subirrigated meadows without affecting later biomass production and result in improvements in forage quality. In addition, we hypothesized that post-burn grazing would lower future biomass production while improving forage quality at the end of the season.

Materials and Methods

Study site weather

Research was carried out at the University of Nebraska Gudmundsen Sandhills Laboratory (GSL) located 11 km northeast of Whitman, Nebraska (lat 42°03’34.9”N, long 101°24’52.1”W, elevation 1,068 m). The study took place in years 2017, 2018, and 2019. The 32-year average annual precipitation for GSL is 500 mm (HPRCC, 1987-2019). In the study years (2017, 2018, and 2019) annual precipitation was 544 mm, 716 mm, and 732 mm, respectively (Figure 2.1). In the Nebraska Sandhills, approximately 75% of yearly precipitation occurs during the growing season spanning April-September (Wilhite & Hubbard, 1990). Growing season precipitation averages 405 mm, and in the study years 2017, 2018, and 2019 it was 412 mm, 521 mm, and 583 mm, respectively (Figure 2.1). January is often the coldest month with an average of -3.9°C, while July is the warmest with a temperature average of 22.2°C.

Soil type

The soils of the low-lying subirrigated meadow pasture are poorly drained. During wet periods, standing water is present on the lower elevation regions of the meadow. The major soil at the site is Crowther loam (Web Soil Survey, NRCS-USDA). This soil has loam, sandy clay loam, and loamy sand in its profile. The parent material is calcareous loamy aeolian deposits over calcareous sandy aeolian deposits. Minor soil components include Valentine-Tryon and Valentine-Dunday both made up of fine and loamy sand derived from wind-blown sand deposits.

Study site description

The study took place on areas within a 58 hectare subirrigated meadow pasture dominated by perennial cool-season graminoids. This meadow had a history of being rotationally grazed by cattle during the growing season for the previous three years before the onset of the study. Common species at the site included sedges (*Carex* spp.), with Nebraska sedge (*Carex nebrascensis* Dewey) being the most prevalent sedge. In addition, there were rushes (*Scirpus* spp.), spikerushes (*Eleocharis* spp.), Kentucky bluegrass (*Poa pratensis* L.), and quackgrass (*Elymus repens* (L.) Gould). Native warm-season grass species included big bluestem (*Andropogon gerardii* Vitman), switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* (L.) Nash), and prairie cordgrass (*Spartina pectinata* Bosc ex Linx). Forbs made up a small component and included Missouri goldenrod (*Solidago missouriensis* Nutt.), horsetail (*Equisetum laevigatum* A. Braun), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.) and alsike clover (*Trifolium hybridum* L.).

Experimental Design

Our research created plots (0.00366 to 0.00506 ha) within a subirrigated meadow in a randomized complete block design separated into two strip plots. The randomized complete block design was used to capture the effects of early season burning, mowing, and an untreated control on later forage production and quality. During the early growing season, cattle also grazed on the larger meadow area, presenting an additional opportunity to study a potential treatment by grazing interaction. In meeting this additional objective, we split our main study plot into two strips, an ungrazed strip and a grazed strip. This resulted in a randomized complete block design implemented across two adjacent strip plots (Figure 2.2).

First, within years, four blocks were randomized to include an early season burn, mow, and control treatments for a total of 12 plots. Plots measured 3.0 x 12.2 m in 2017, and were increased to 6.1 x 18.3 m in the subsequent years. Early season burning, mowing or a non-treated control were administered to the plots on 8 May 2017, 1 May 2018, and 5 May 2019. Location of the main study area was changed each year on the same meadow but study areas were within 0.40 km of one another.

Across years, burns were administered during the time of 1300-1600 hours. Relative humidity during the burns ranged from 40-60%, while temperatures ranged from 23.9 - 29.4°C. Fuel loads for the 2017, 2018, and 2019 study years were 4,518 ± 746, 4,271 ± 896, and 3,772 ± 1,724 $\text{kg}\cdot\text{ha}^{-1}$ (mean ± 1 SD), respectively. The mowing treatment was applied with a hand push mower that cut the vegetation to a 60 mm stubble height. All residue from mowing was left in the plots.

To examine the potential compounding effects of early-season burning and grazing, our main study plot was split into two strips, a grazed strip and an adjacent ungrazed strip (Figure 2.2). This division resulted in subplots (e.g. burned/grazed, burned/ungrazed). An electrical fence was placed around the ungrazed strip. During the study, 140-180 mature cows freely graze on the assigned grazed strip while also having continued access to the rest of the meadow pasture. Cattle grazed from shortly after treatments were applied in early-May until early-June, for approximately one month (87 – 112 $\text{AUD}\cdot\text{ha}^{-1}$). The grazed strip was ungrazed following cattle removal in early-June.

Vegetation Sampling

Vegetation sampling was carried out after cattle were removed from the meadow in June (6 June 2017; 12 June 2018; and 10 June 2019). Vegetation biomass was collected from all subplots in the grazed and ungrazed areas by randomly placing three 0.25 m^2 quadrats in each plot and clipping all plant material at ground level. Vegetation was separated into total live (cool-season graminoids, warm-season grasses, and forbs) and dead plant material. Dead plant material sampling in 2017 and 2018 included only standing dead plant material, but in 2019 sampling included both standing dead and litter plant material. Following grazing in June, utilization was also obtained on the study plots. Differences in total live standing forage between the ungrazed strip subplot and the adjacent grazed strip subplot represented utilization for each treatment plot.

Plant biomass samples were taken again in August (21 August 2017; 13 August 2018; and 19 August 2019) when vegetation was at peak standing biomass to arrive at end of season forage production. Similar to June, three 0.25m^2 quadrats were randomly placed in each plot and aboveground vegetation was clipped at ground level. In August, samples were separated into plant functional groups that included cool-season graminoids (grasses, sedges, and rushes), warm-season grasses, forbs, and dead. Similar to the June sampling; standing dead was only collected in 2017 and 2018 and both standing dead and litter were collected in 2019. Each sample was dried for 48 hours at 60°C before being weighed. Total live weight was also recorded by combining dry weight of cool-season graminoids, warm-season grasses, and forbs from each plot.

Cool-season graminoids and warm-season grasses from each subplot from the August sample period were ground through a 1 mm screen and then sent to Ward Labs

(Kearney, NE) for forage quality analysis. Near infrared reflectance spectroscopy (NIRS) was used to determine crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and total digestible nutrients (TDN). Additionally, forage samples were analyzed for macro and micro minerals using wet chemistry with the results reported in the supplemental materials.

Statistical analysis

All data were analyzed using SAS 9.4 (Cary, North Carolina, USA). June and August data were analyzed separately using a mixed model analysis of variance (ANOVA) with the SAS PROC GLIMMIX statement. Fixed effects for June utilization included year, treatment, and the year by treatment interaction. Random variables for utilization were block within year and treatment by block within year. June live and dead plant material biomass was evaluated with the fixed effects of year, grazing, treatment and the grazing by treatment interaction. Random variables included block within year, grazing within year (to account for the experimental design of including strips with and without grazing), and treatment by block within year. August forage biomass production of all plant functional groups (cool-season graminoids, warm-season grasses, forb, total live and dead), forage quality measurements (CP, ADF, NDF, and TDN) and minerals followed the same analysis. Effects for all tests were considered significant at a P-value of 0.05, while tests with P-values between 0.05 and 0.10 were considered trending significant. Both significant and trending effects were further examined with pairwise comparisons using the LSMEANS statement.

Results

June biomass

Utilization in early-June following grazing was 53% greater in the burned plots and 30% greater in the mowed plots ($P < 0.01$) compared to the control (Fig. 2.3). Early-June live biomass was influenced by the main effects of treatment ($P < 0.01$) and grazing ($P = 0.02$), but we did not detect a grazing by treatment interaction ($P = 0.63$). Spring burning reduced June live biomass 36%, while mowing led to a 25% reduction compared to the un-burned control (Fig. 2.4). Averaged across all treatments, live biomass production was reduced with early-season grazing by 61% relative to ungrazed plots (Fig. 2.5).

Burning and mowing both successfully removed dead plant material from meadows ($P < 0.01$). In contrast to the control, burned plots had 82% less dead plant material while mowed plots had 67% less (control 1,059; burn 193; mow 354 ± 147 $kg \cdot ha^{-1}$). A treatment by grazing interaction was also detected ($P = 0.05$; Fig. 2.6). This interaction was driven by the large difference in dead material between the grazed and ungrazed control treatment plots (grazed control, 1,272 $kg \cdot ha^{-1}$; ungrazed control, 846 ± 175 $kg \cdot ha^{-1}$). No significant differences in dead material were detected between the grazed and ungrazed plots of either the burned or mowed plots ($P \geq 0.90$).

August live biomass

While June live biomass was significantly reduced by spring burning or mowing, the effects of these practices did not carry over into August live biomass ($P = 0.30$; Fig. 2.7). When averaged over grazed and ungrazed plots, growth of meadow biomass in August did not differ across study treatments (Fig. 2.7). Though not statistically significant (P = 0.21), grazing from early-May to early-June lowered total live biomass production in August by a mean of 29% (1,507 ± 833 kg·ha^{-1}) across the three study years (Fig. 2.8).

August cool-season graminoid biomass

Cool-season graminoid biomass was not different among the burned, mowed, and control treatments (P = 0.31; Fig. 2.7). Cool-season graminoid biomass was influenced by both year and grazing but there was no interaction between the two effects (year main effect: P = 0.03; grazing main effect: P = 0.02). Production of cool-season graminoids in the meadow plots was significantly lower in year 2018 than 2017 or 2019 (3,476, 1,883, and 3,221 ± 157 kg·ha^{-1}) respectively. Early-season grazing reduced production of cool-season graminoids by 23% compared to ungrazed treatments (Fig. 2.8).

Warm-season grass biomass

Warm-season grass biomass was not significantly different among the burned, mowed, and control treatments (P = 0.96; Fig. 2.7). Grazing reduced warm-season grass production by 38%, but a large standard error (± 462 kg·ha^{-1}) and a high amount of yearly variation (e.g., 1,850 kg·ha^{-1} in 2019 and 717 kg·ha^{-1} in 2018) contributed to no statistical difference between the grazed and ungrazed strips (P = 0.41; Fig. 2.8).

Forb biomass

Forb biomass production was not statistically different between the control, burned, or mowed plots (P = 0.82; Fig. 2.7), or between grazed and ungrazed plots (P = 0.41; Fig. 2.8).

Dead plant biomass

Similar to June, biomass of dead plant material on the meadow was greater in the control than the burned or mowed plots ($P < 0.01$, Fig. 2.7).

Cool-season graminoid forage quality

Relative to the control, burning and mowing did not significantly improve any of the measured forage quality variables (CP, ADF, NDF, or TDN) for cool-season graminoids ($P \geq 0.15$; Table 2.1). Nonetheless, a trend existed for the main effects of year ($P = 0.10$) and grazing ($P = 0.07$) to influence cool-season graminoid CP concentrations. Crude protein was 1.71 percentage units higher in 2018 than 2019, but not significantly different from crude protein values in 2017. Grazing led to an average increase of crude protein of 1.04 percentage units compared to plots that were ungrazed. Grazing also lowered ADF 1.04 percentage units, while increasing TDN 1.96 percentage units relative to ungrazed plots.

Warm-season grass forage quality

Similar to cool-season graminoids, warm-season grass crude protein was not significantly affected by spring burning or mowing ($P = 0.20$; Table 2.2). Unlike cool-season graminoids, main effects of year and grazing ($P = 0.33$ and 0.23, respectively) did not have an influence on warm-season grass crude protein. However, ADF and TDN energy values were generally affected by treatment, year, and grazing main effects (Table 2.2). NDF was influenced by a year main effect ($P = 0.04$) and had a tendency of being influenced by treatment ($P = 0.10$). Relative to controls, mowing reduced ADF by 0.14 percentage units and increased NDF by 1.28 percentage units while burning reduced both ADF and NDF by 1.04 and 0.79 percentage units, respectively. Treatment led to corresponding differences in TDN (P=0.01), whereby increases in TDN from the control were greatest in burned plots (1.16 percentage units) and negligible in mowed plots (0.15 percentage units). Similarly, grazing generally improved energy value, decreasing ADF and NDF by 1.67 and 1.39 percentage units respectively, and increasing TDN by 1.89 percentage units.

Discussion

Prescribed burning early in the growing season has potential to reduce dead plant material without negatively affecting hay production later in the growing season on subirrigated meadows in the Sandhills. In support of our original hypothesis, burning was effective in removing undesirable dead plant material from meadows without reducing end of season total live biomass. Our hypothesis that spring burning would increase forage quality was supported for warm-season grasses but was not for cool-season graminoids. Early-season grazing had more of an influence on end of season plant biomass and quality than did spring burning.

Burning and mowing effects on plant biomass

Burning and mowing were both successful in removing dead plant material from meadow sites in both grazed and ungrazed areas. Burning is usually the most effective method for dead plant removal, though both burning and mowing have been shown to be effective practices to reduce dead plant material in tallgrass (Dickson, 2019; Schacht et al. 1998) and mixed-grass prairie (Vermeire et al. 2020). A trend was present for dead plant biomass to vary between years, which was the result of differences in dead material sampling method between years. Study year 2019 saw significantly more dead material than previous years due to the collection of both standing dead and litter. Nonetheless, the direction of the effects of the spring treatments were similar across all years of the study.

Neither spring burning nor mowing had an effect on end of season production of total live, cool-season graminoids, warm-season grass, or forb production compared to the non-treated control. Similarly, other studies have reported that burning or mowing did not influence annual plant production (Vermeire et al. 2020; Bennett et al. 2019). On a reconstructed tallgrass prairie in Nebraska, burning resulted in greater end of season production than mowing (Dickson, 2019). However, in these same studies shifts in species composition from burning or mowing were noted. In our study, spring burning and mowing had no effect on both cool-season graminoids and warm-season grasses in mid-August. Because burning coincides with early growth and establishment of cool-season species, spring burns often favor warm-season grasses at the expense of cool-season grasses (Bennett et al. 2019; Bouressa et al. 2010; Howe, 2000). In another mesic grassland with sandy loam soils, two alternate year spring burns resulted in persistence of warm-season grasses in a former cool-season monoculture of *Phalaris arundinacea* L. (Howe, 2000). However, the use of spring burning for persistence of warm-season grasses in cool-season dominated sites seems to require follow-up burns (Bennett et al. 2019; Bouressa et al. 2010; Howe, 2000) where in our study post-burn production response was limited to only one growing season.

Early-season grazing effects on plant biomass

Relatively heavy grazing in the early growing season acted independently of spring burning or mowing to influence end of season production. In our study, a significant impact from grazing was only detected on biomass production of cool-season graminoids. Still, grazing did lead to large reductions in production of total live (1,507 ± 599 kg·ha^{-1}) and warm-season grasses (670 ± 462 kg·ha^{-1}). The low statistical power of grazing (df = 2, grazed and ungrazed strips), along with large standard errors, likely prevented detections of statistical significance. Past research on Sandhills subirrigated meadows has shown that May grazing reduced hay yields by half (4,000 kg·ha^{-1} to 2,000 kg·ha^{-1}; Horney, 1999). Volesky et al. (2005) found that early-May grazing of upland range in the Sandhills significantly lowered the production of cool-season species in August, similar to what we found in our study. Grazing cool-season species in early-May in the Sandhills can be especially damaging because it occurs during a time of rapid growth and development. Research of sedge dominated Tibetan alpine swamp meadows in China and high elevations meadows in Idaho, shows grazing during the growing season can lead to significant reductions in end of season production (Tian et al. 2020; Clary, 1995). Compaction from heavy spring grazing was a contributing factor for a later decrease in plant height and production on meadows in Idaho, USA (Clary 1995). After all is considered, we are cautious to report that spring grazing does not affect total biomass production given the relatively large reductions of live biomass and significant reductions in cool-season graminoid biomass we witnessed. Therefore, we believe further research into spring grazing effects on later biomass production is warranted.

Interacting effects of spring management with grazing

Spring burning or mowing of meadows did not interact with grazing to influence end of season biomass production. In shortgrass steppe, grazing the first-growing season following fire did not lower production despite below-average precipitation (Augustine et al. 2010). In contrast, grazing the first growing season post-burn on uplands in northern mixed-grass prairie lowered production (Gates et al. 2017). However, subsequent grazing the second growing season post-burn resulted in similar production between grazed and rested sites (Gates et al. 2017). In comparison to burned-grazed treatments, burned only treatments had higher native grass tiller density and cover on a Wisconsin cool-season meadow pasture interseeded with warm-season grasses (Bouressa et al. 2010). When patch-burn grazing was applied in tallgrass prairie there was also a loss of native grass cover in burned-grazed patches (Fuhlendorf and Engle, 2004). Importantly, the authors note that decreasing grass cover allowed for increases in forbs, which in turned helped to increase overall heterogeneity in the grassland. In our study, forb biomass in grazed-burned treatments was no different from the control. Wet conditions on Sandhills meadows may help to buffer against negative effects from defoliation and limit shifts in graminoid dominance with fire and heavy grazing early in the growing season. Volesky et al. (2011) subjected common subirrigated meadow species, (Nebraska sedge, slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners) and birdsfoot trefoil (*Lotus corniculatus* L.) to varying defoliation frequencies (two or five times during the growing season) and intensities (light or heavy). Neither defoliation frequency nor intensity affected aboveground production of the three species later in the growing season.

The effects of burning on forage quality

The use of prescribed burning in cattle production systems should be considered given fire's ability to improve forage quality and lead to increases in cattle weight gains (Limb et al. 2011; McGinty et al. 1983). In our study, relative to mowing, burning increased quality of warm-season grasses by increasing TDN and lowering fiber fractions

(ADF and NDF). Vermeire et al. (2020) also found burning increased forage quality to a greater extent than mowing. Fire can enhance quality of regrowth through deposition of nutrient rich ash or its ability to increase soil mineralization (Dhillion and Anderson, 1993; Frost and Robertson, 1987). In addition, burn regrowth results in vegetation that has a higher leaf to stem ratio (Frost and Robertson, 1987), whereby the nutritive value of leaves is higher than any other plant part (Arzani et al. 2004).

Spring burning increased end of season forage quality of warm-season grasses, but not cool-season graminoids. Because of inherent differences in photosynthesis, cool-season graminoids were more advanced in maturity than warm-season grasses when samples were clipped in August. In the Nebraska Sandhills, native cool-season perennial grasses begin growth in mid- to late-March and reach maturity by late-June. In contrast, native warm-season grasses often begin growth in early-May and remain actively growing until late-August. It is generally true that forage quality of both groups declines from June to September in the Sandhills (Nichols et al. 1993). However, burning did result in improved TDN for warm-season grasses, which may indicate that burning improved quality by delaying maturity of these species. However, differences in TDN between burned and other treatments were relatively small.

Forage quality improvements from burning are usually short-lived (Dhillion and Anderson, 1993; Frost and Robertson, 1987). In an East African savanna, an increase in plant nutrients (N, P, K, Ca and Mg) occurred one-month post-burn but by three months nutrients levels were similar to the control (van de Vijver et al. 1999). The authors report short-term increases in quality were due to increased leaf to stem ratio and reduced maturity of plants of post-burned vegetation. Similarly, we generally saw no differences in mineral concentrations between burned or un-burned control plots three months post-burn (Table 2.1S and 2.2S, supplemental material). Increased cattle grazing utilization of the burn and mow plots compared to the control indicate there may have been some short-term increases in overall quality of vegetation following these disturbances.

Our results revealed cattle utilization of the defoliated (burned and mowed) plots was higher than the control. This suggests cattle selected for the higher quality regrowth with less standing dead plant material after these disturbances. In the tallgrass prairie, cattle spend up to 75% of their time grazing the higher quality regrowth of burned areas when allowed access to both unburned and burned areas (Kerby et al. 2007; Fuhlendorf and Engle, 2004). At our smaller plot scale, evidence supports selective cattle utilization on burned areas is greater than adjacent non-burned areas in close proximity. As a result, cattle behavior response should be considered when prescribed burning only a portion of an area in a patch-burn framework.

The effect of grazing on forage quality

Generally, grazed plots showed slightly higher quality CP and TDN values than ungrazed plots in August. Nonetheless, improvements in quality were still not enough to meet the nutritional requirements of a mature cow either in the last third of her pregnancy (7.9% CP, 54% TDN) or during the first 30 days of lactation (10.6% CP, 58% TDN; Lalman & Richards, 2017). Horney (1999) found that grazing subirrigated Sandhills meadows during May increased crude protein concentration of forage by early-August, but to a greater extent than our study (May-grazed, 16% CP; ungrazed 9% CP). Earlier harvesting along with sampling of a more diverse array of meadow species by Horney, 1999 may explain why our study saw less improvement in quality with grazing. Another study at the Gudmundsen Sandhills Laboratory found that September regrowth of mid-June harvested meadow had about 8% crude protein (Reece et al. 1994). Further delays of initial harvest dates to mid-July or mid-August resulted in crude proteins values of September regrowth increasing to values of 10% and 13% CP, respectively (Reece et al. 1994). Thus, defoliated plants often have higher crude protein than non-defoliated plants due to a delay in plant phenology and the fact that younger plants have more leaf tissue than stems (Arzani et al, 2004).

As our study revealed, grazing vegetation can have tradeoffs in quality and quantity. Grazing early in the growing season tended to improve forage quality but reduced plant production, which is similar to results reported by Horney, (1999) for Sandhills meadows and Tahmasebi et al. (2020) on steppe rangeland in Iran. May grazing, when followed by sufficient recovery time, can be an economical and important management consideration for Sandhills ranching operations. Grazing meadows during May in the Sandhills, while upland range is dormant, reduces fed hay cost and increases profitability of ranching operations (Adams et al. 1994). However, persistent overgrazing of meadows should be avoided as it can lead to accelerated gullying, compaction and lowering of the water table (Clary, 1995; Bartolome, 1984).

Management implications

Our research suggests that burning subirrigated meadows in the spring is a suitable management option for rangeland managers in the Nebraska Sandhills to remove litter and standing dead plant material without negatively affecting hay production later in the growing season. Grazing from early-May to early-June will likely decrease forage production later in the growing season regardless of treatment. However, early spring grazing often provides a high-quality forage to cattle in the spring before upland range green up, and this defoliation of vegetation can lead to a better quality hay at the end of the season. Future work on subirrigated meadows should examine the impacts of different grazing intensities on burn regrowth forage production and quality and examine the effects on burning and grazing on soil factors such as compaction and infiltration at larger production scales.

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Tables and Figures

Table 2.1. Least square means ±SE results from a mixed model ANOVA for the effects of year (2017, 2018, 2019), grazing (grazed, ungrazed) and treatment (control, burn, mow) on forage quality measurements of cool-season graminoids from samples collected at peak standing crop in August.

	Year					Grazing				Treatment				
Measurement[1]	**2017**	**2018**	**2019**	SE	*P-value*	**Grazed**	**Ungrazed**	SE	*P-value*	**Control**	**Burn**	**Mow**	SE	*P-value*
CP (%DM)	6.55 ab[2]	7.90 a	6.19 b	0.29	0.10	7.40 a	6.36 a	0.22	0.07	6.78	6.92	6.94	0.28	0.15
ADF (%DM)	40.96	40.55	40.74	0.29	0.67	39.90 b	41.60 a	0.2	0.02	41.17	40.48	40.6	0.29	0.35
NDF (%DM)	65.33	66.13	64.13	0.81	0.40	64.62	65.77	0.62	0.29	65.71	64.67	65.2	0.56	0.96
TDN (%DM)	55.85	56.32	56.1	0.33	0.66	57.07 a	55.11 b	0.23	0.01	55.61 b	56.4 a	56.25a	0.33	0.22

[1] Measurement indicates CP=crude protein, ADF=acid detergent fiber, NDF=neutral detergent fiber, TDN=total digestible nutrients, all of which are on a percent dry matter basis.

[2] Different letters within a row represent significant differences between the means of the respective year, grazing, and treatment main effects for the forage quality measurement at $P \leq 0.10$.

Table 2.2. Least square means ±SE results from a mixed model ANOVA for the effects of year (2017, 2018, 2019), grazing (grazed, ungrazed) and treatment (control, burn, mow) on forage quality measurements of warm-season grasses from samples collected at peak standing crop in August.

	Year					Grazing				Treatment				
Measurement[1]	**2017**	**2018**	**2019**	SE	*P-value*	**Grazed**	**Ungrazed**	SE	*P-value*	**Control**	**Burn**	**Mow**	SE	*P-value*
CP (%DM)	5.83	6.66	5.38	0.45	0.33	6.34	5.58	0.34	0.23	5.83	6.22	5.82	0.3	0.20
ADF (%DM)	42.25 a[2]	41.60 a	39.94 b	0.28	0.05	40.43 b	42.10 a	0.02	0.02	41.66 a	40.62 b	41.52 a	0.26	0.01
NDF (%DM)	71.10 a	69.03 a	64.34 b	0.74	0.04	67.46	68.85	0.51	0.12	67.99 ab	67.20 b	69.27 a	0.68	0.10
TDN (%DM)	54.39 b	55.12 b	57.01 a	0.31	0.05	56.45 a	54.56 b	0.23	0.02	55.07 b	56.23 a	55.22 b	0.29	0.01

[1] Measurement indicates CP=crude protein, ADF=acid detergent fiber, NDF=neutral detergent fiber, TDN=total digestible nutrients, all of which are on a percent dry matter basis.

[2] Different letters within a row represent significant differences between the means of the respective year, grazing, and treatment main effects for the forage quality measurement at $P \leq 0.10$.

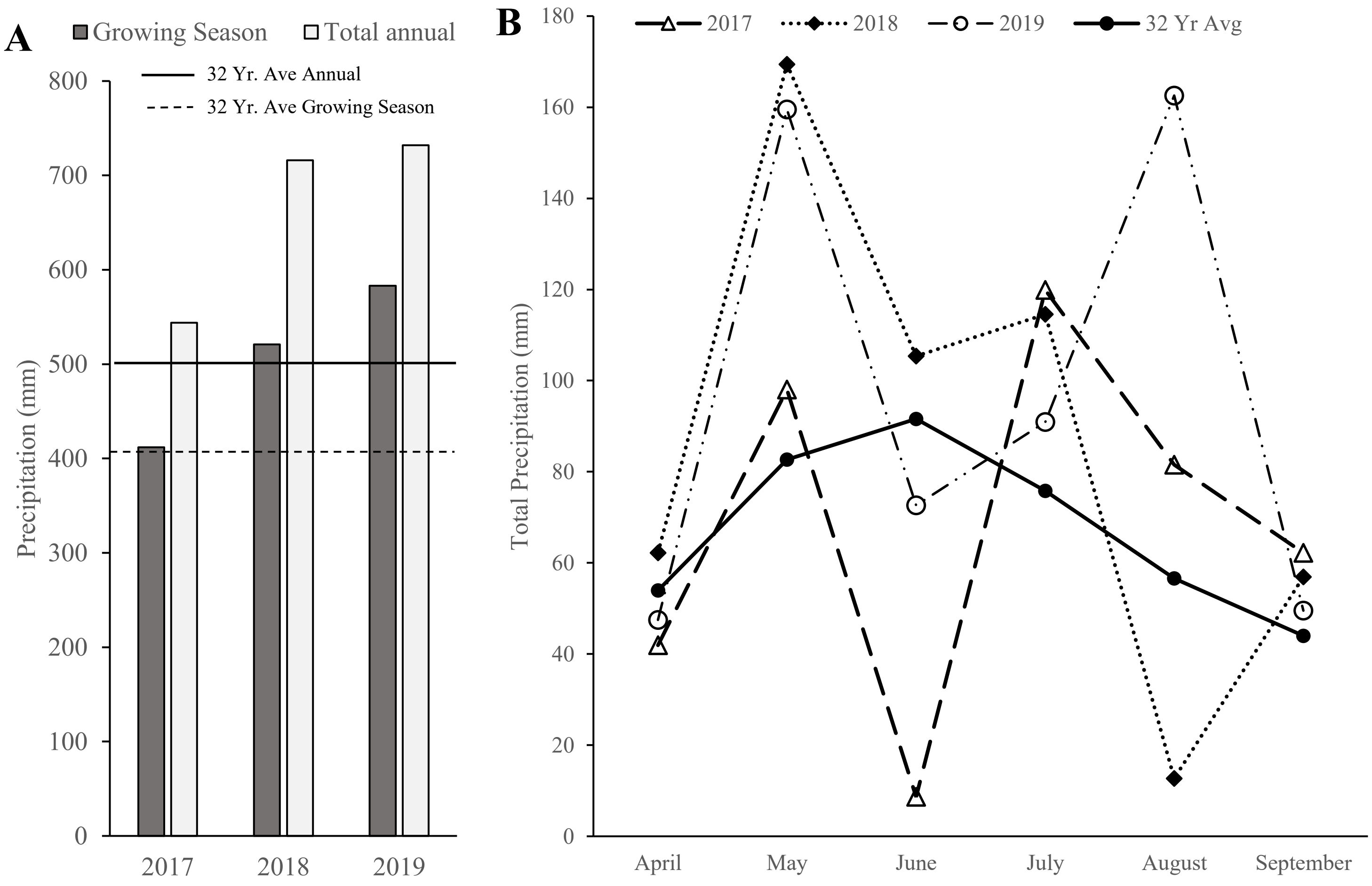

Figure 2.1. Total accumulated precipitation (A) and growing season precipitation for the 2017, 2018, and 2019 study years (B) at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska. Data obtained from High Plains Regional Climate Center (HPRCC).

	Block 1			Block 2			Block 3			Block 4		
Grazed	M	B	C	B	M	C	C	B	M	B	C	M
Ungrazed	M	B	C	B	M	C	C	B	M	B	C	M

Figure 2.2: Experimental design. Note this diagram represents randomization from only one study year and that grazing (grazed and ungrazed) and treatments within blocks (C=control, B=burn, M=mow) were randomly assigned each year.

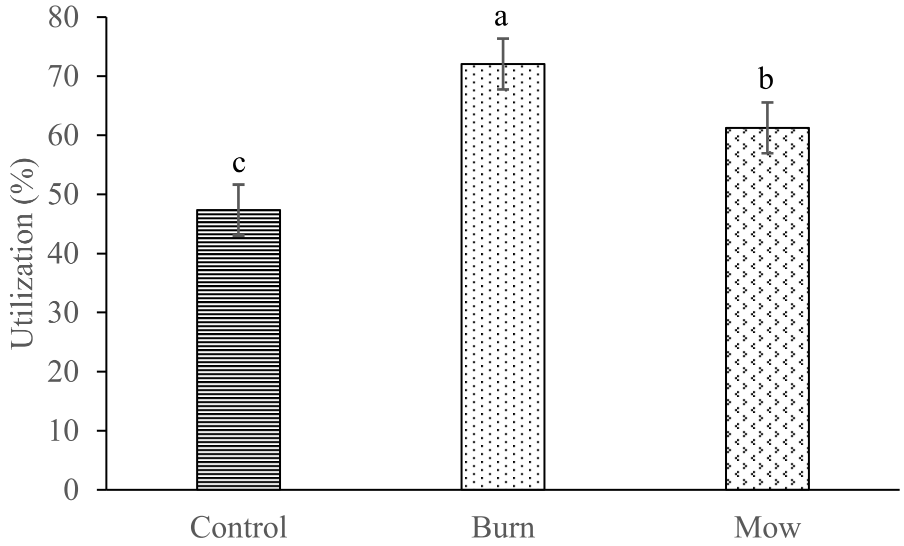

Figure 2.3. Mean utilization for all treatments (control, burn, mow) taken after cattle grazing in early-June in 2017, 2018, and 2019. Error bars are ±SE of least square means. Different letters across treatments indicates significant differences in grazing utilization at $P \leq 0.07$ based on the least square means comparison method. Samples were collected from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

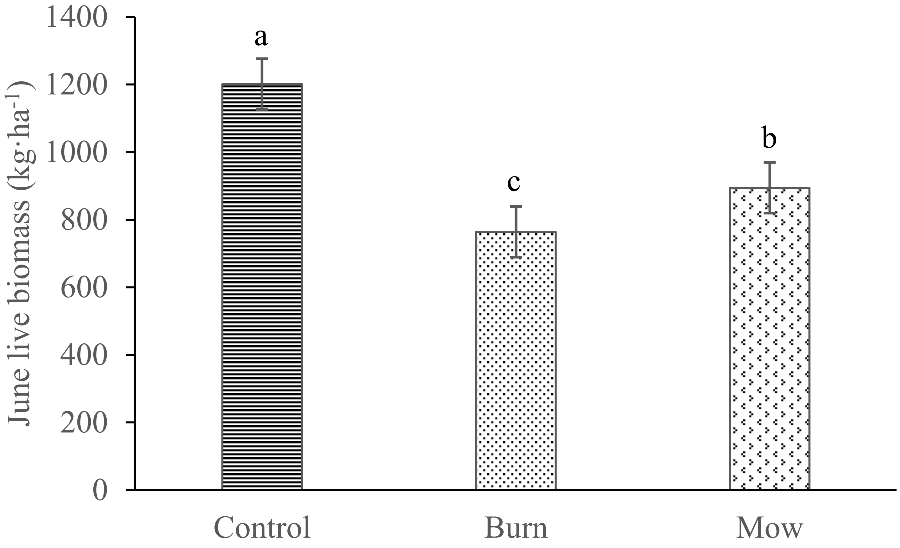

Figure 2.4. Mean June live biomass for the control, burn, and mow plots averaged across years and grazing. Standard error bars are ±SE of least square means. Different letters indicate significant treatment differences at $P \leq 0.08$ based on the least square means simple effects comparison method. Samples were collected in June, after cattle grazing, from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

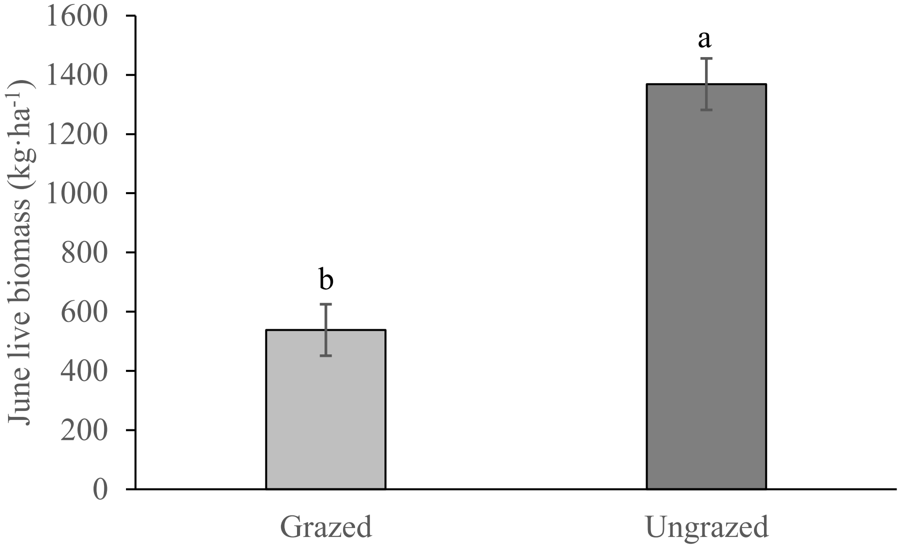

Figure 2.5. Mean June live biomass averaged across years and treatments for grazed and ungrazed strip plots. Standard error bars are ±SE of least square means. Different letters indicate differences between grazed and ungrazed plots at $P \leq 0.02$, based on least square means simple effects comparison method. Samples were collected in June, after cattle grazing, from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

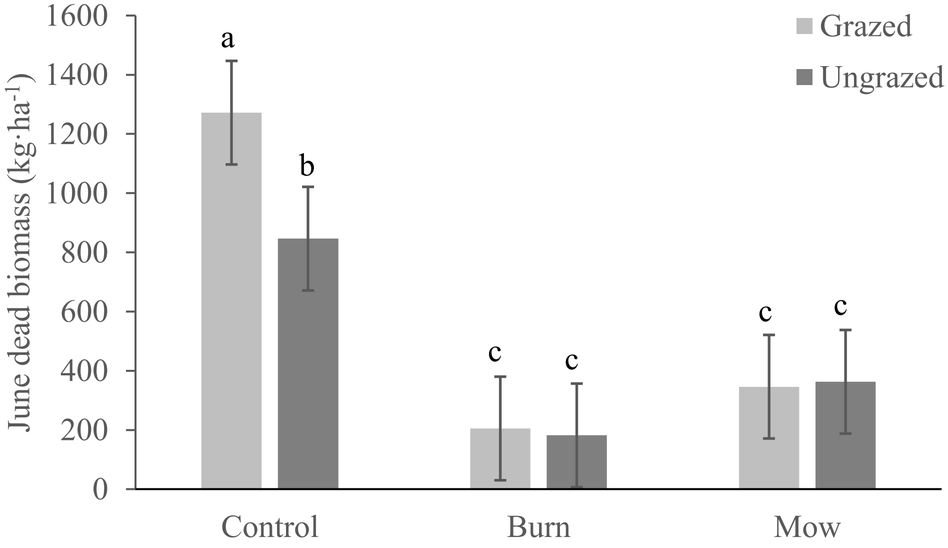

Figure 2.6. Mean June dead biomass for the respective treatments and grazing events averaged across years. Standard error bars are ±SE of least square means. Different letters within treatments indicate significant differences between the grazed and ungrazed plots at $P \leq 0.03$, based on least square means simple effects comparison. Samples were collected in June, after cattle grazing, from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

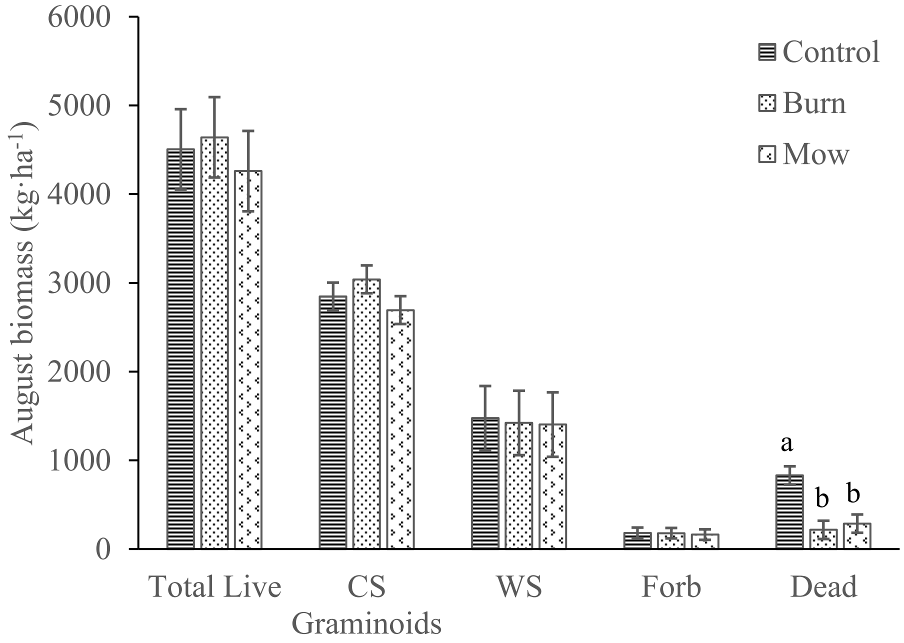

Figure 2.7. Main treatment effect of August biomass for the respective plant functional groups and treatments averaged across grazing events and years. Standard error bars are ±SE of least square means. Different letters within plant functional group indicates treatment differences at $P < 0.01$, based on least square means simple effects comparison method. Samples were collected in August when vegetation was at peak standing crop from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

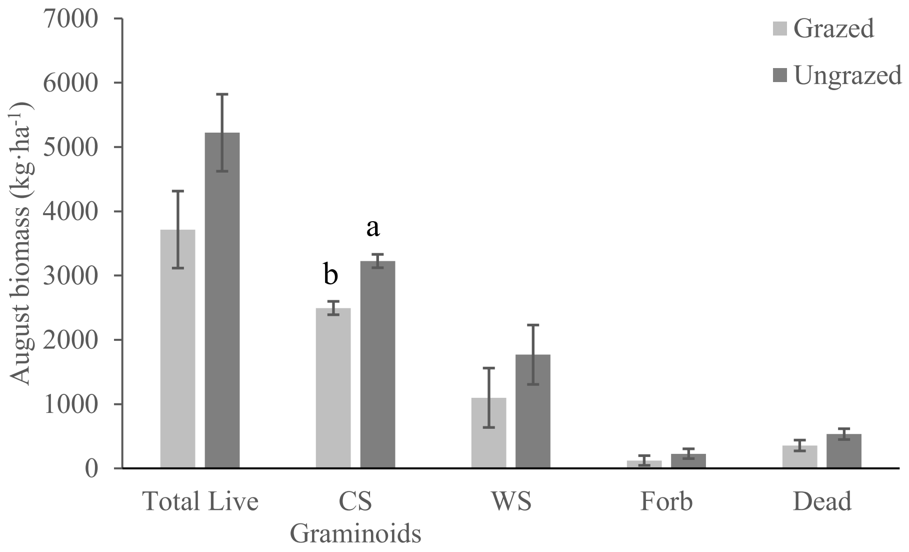

Figure 2.8. Grazing main effect for August biomass of the respective plant functional groups and grazing events averaged across years. Standard error bars are ±SE of least square means. Different letters within plant functional group indicate differences between grazed and ungrazed plots at P = 0.02, based on least square means simple effects comparison method. Samples were collected in August when vegetation was at peak standing crop from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

Supplemental Materials

Table 2.1S. Least square means ±SE results from a mixed model ANOVA for the effects of year (2017, 2018, 2019), grazing (grazed, ungrazed) and treatment (control, burn, mow) on forage mineral measurements of cool-season graminoids from samples collected at peak standing crop in August.

	Year					Grazing				Treatment				
Mineral	**2017**	**2018**	**2019**	SE	*P-value*	**Grazed**	**Ungrazed**	SE	*P-value*	**Control**	**Burn**	**Mow**	SE	*P-value*
Ca (%)	0.70	0.76	0.68	0.06	0.66	0.72	0.70	0.04	0.84	0.68 b[1]	0.73 a	0.73 a	0.04	0.08
K (%)	1.26 a	1.46 a	0.91 b	0.07	0.06	1.23	1.18	0.05	0.44	1.21	1.20	1.13	0.05	0.93
Mg (%)	0.15 b	0.14 b	0.22 a	0.01	0.10	0.17	0.17	0.01	0.90	0.16 b	0.17 ab	0.18 a	0.01	0.05
Na (%)	0.08	0.07	0.06	0.02	0.79	0.08	0.06	0.01	0.28	0.07	0.07	0.07	0.01	0.63
P (%)	0.11 b	0.13 a	0.11 b	0.00	0.03	0.12 a	0.11 b	0.00	0.04	0.11 b	0.11 b	0.12 a	0.00	0.01
Cu (ppm)	4.83 b	4.71 b	6.58 a	0.22	0.04	5.48	5.27	0.16	0.40	5.38	5.33	5.42	0.18	0.92
Fe (ppm)	58.71 b	57.54 b	83.42 a	3.50	0.05	68.31	64.81	2.86	0.48	62.46	67.63	69.58	3.37	0.31
Mn (ppm)	222.79 b	350.67 a	124.00 b	32.57	0.08	235.06	229.92	20.91	0.81	247.87	221.75	227.83	22.21	0.42
S (ppm)	0.21 a	0.20 a	0.11 b	0.01	0.05	0.18	0.17	0.01	0.36	0.17	0.18	0.18	0.01	0.64
Zn (ppm)	10.35 b	12.26 a	12.55 a	0.44	0.12	11.95	11.48	0.30	0.29	11.19	11.96	11.99	0.39	0.22

[1] Different letters within a row represent significant differences between the means of the respective year, grazing, and treatment main effects for the forage mineral measurement at P ≤ 0.10.

Table 2.2S. Least square means ±SE results from a mixed model ANOVA for the effects of year (2017, 2018, 2019), grazing (grazed, ungrazed) and treatment (control, burn, mow) on forage mineral measurements of warm-season grasses from samples collected at peak standing crop in August.

	Year					Grazing				Treatment				
Mineral	**2017**	**2018**	**2019**	SE	*P-value*	**Grazed**	**Ungrazed**	SE	*P-value*	**Control**	**Burn**	**Mow**	SE	*P-value*
Ca (%)	0.57	0.66	0.58	0.02	0.18	0.60	0.60	0.02	0.88	0.60	0.62	0.59	0.02	0.77
K (%)	1.07 a[1]	1.17 a	0.56 b	0.06	0.03	0.94	0.93	0.04	0.83	0.94	0.93	0.94	0.04	0.95
Mg (%)	0.18 b	0.18 b	0.27 a	0.02	0.12	0.21	0.21	0.01	0.71	0.20	0.21	0.21	0.01	0.54
Na (%)	0.02	0.02	0.02	0.00	0.97	0.02	0.02	0.00	0.27	0.02	0.02	0.02	0.00	0.51
P (%)	0.11 ab	0.13 a	0.10 b	0.01	0.12	0.12	0.11	0.00	0.43	0.11	0.11	0.12	0.00	0.46
Cu (ppm)	5.83	5.30	5.01	0.45	0.54	5.28	5.48	0.32	0.66	5.56	5.19	5.39	0.29	0.26
Fe (ppm)	50.00 b	58.46 b	100.38 a	7.05	0.06	70.03	69.19	5.30	0.91	66.88	65.42	76.54	6.59	0.42
Mn (ppm)	55.46 b	99.17 a	46.75 b	9.17	0.10	67.39	66.86	5.92	0.93	73.54	68.50	59.33	7.72	0.35
S (ppm)	0.15 a	0.14 ab	0.10 b	0.01	0.17	0.12	0.13	0.01	0.41	0.12	0.13	0.13	0.01	0.57
Zn (ppm)	14.90	14.74	15.00	0.81	0.98	15.53	14.21	0.54	0.14	14.13 b	14.74 ab	15.74 a	0.66	0.15

[1] Different letters within a row represent significant differences between the means of the respective year, grazing, and treatment main effects for the forage mineral measurement at P ≤ 0.10.

CHAPTER 3: THE EFFECTS OF PRE-FREEZE AND POST-FREEZE GRAZING ON SUBSEQUENT YEAR HAY PRODUCTION AND QUALITY ON SUBIRRIGATED MEADOWS

Introduction

Subirrigated meadows make up about 10% of the approximately 5.5 million ha of the Nebraska Sandhills (Healey et al. 2011). High forage productivity on these meadows is possible because the water table is within rooting depth of plants during most of the growing season. The primary use of these meadows for ranches in the Sandhills is hay production, which often occurs in July when the meadows have become dry enough for haying equipment to enter. Grazing of regrowth after haying is a common management practice in the region employed by more than half of operations with meadows (Coady and Clark, 1993). Grazing of hay regrowth commonly begins in October and lasts for about a month (Coady and Clark, 1993). Ranchers often graze meadow regrowth with newly weaned calves. Winter grazing is also practiced and typically begins in November and lasts until March (Coady and Clark, 1993).

In the fall, cool-season species that dominate meadows provide high-quality forage at a time when warm-season grass dominated upland range is dormant. Adams et al. (1994) studied profitability of wintering systems that grazed either upland range, subirrigated meadows, or fed hay during the winter along with the feeding of hay or grazing of meadows during May. The most profitable system was the grazing of subirrigated meadows during both winter and May. In another study, weaned steer calves either grazed meadow windrows or were fed hay during November-January (Volesky et al. 2002). Total net returns of windrow grazing were higher than bale-fed treatments. Systems that rely more on cattle rather than machines to harvest forage is one method to reduce an operation's feed cost (D'Souza et al. 1990). The results of Adams et al. (1994) and Volesky et al. (2002) show that extending the grazing season with subirrigated meadows in the winter is economical. However, the impacts of winter grazing on subsequent year's hay yield is less understood. In addition, the initiation of grazing on meadows in the fall before complete dormancy of meadow vegetation, and its impact to the subsequent year's hay yields needs further examination.

The objectives of this study were to evaluate the effects of grazing time (pre-freeze or post-freeze) and grazing intensity (heavy or moderate) on the subsequent summer's biomass and forage quality. Here, pre-freeze grazing is defined as grazing initiated in the fall, before the onset of a killing freeze, when meadow vegetation is still green and growing. Post-freeze grazing occurred in the winter after several hard freezes killed aboveground growth of meadow vegetation, leaving vegetation in a dormant state. An ungrazed control was also implemented to determine summer biomass and quality when no management is applied during fall or winter. We hypothesized that pre-freeze grazing would reduce summer biomass but increase forage quality relative to other treatments, while heavy intensity grazing would result in the lowest production in the summer.

Materials and Methods

Study site

A two-year grazing study was conducted at the University of Nebraska Gudmundsen Sandhills Laboratory (GSL) located 11 km northeast of Whitman, Nebraska (lat 42°03’N, long 101°24’W, elevation 1,073 m). Grazing trials were completed on a subirrigated meadow ecological site with a man-made drainage ditch to alleviate flooding. This meadow has a long history of summer haying and fall and winter grazing of regrowth by cattle. Soils at the site are Gannett-Loup fine sandy loam (Web Soil Survey, NRCS-USDA).

The 32-year average annual precipitation for GSL is 500 mm (1987-2019; HPRCC). The months of May, June, and July typically receive 50% of the annual precipitation (250 mm). January is often the coldest month with an average of -2.2°C, while July is the hottest with a temperature average of 21.7°C. The freeze free period for the study region is approximately 130 days (late May to late September).

Cool-season grasses, sedges, and rushes dominate the study meadow. Cool-season grasses include slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners), quackgrass [*Elymus repens* (L.) Gould], redtop bent (*Agrostis stolonifera* L.), timothy (*Phleum pratense* L.), reed canarygrass (*Phalaris arundinacea* L.), creeping meadow foxtail (*Alopecurus arundinaceus* Poir.*)*, Kentucky bluegrass (*Poa pratensis* L.), and smooth bromegrass (*Bromus inermis* Leyss.). Several species of sedges (*Carex* spp. and *Cyperus* spp.), rushes (*Scirpus* spp.), and spikerushes (*Eleocharis* spp.) were prevalent. Warm-season grasses made up a minor component of the plant community and included prairie cordgrass (*Spartina pectinata* Link), switchgrass (*Panicum virgatum*

L.), big bluestem (*Andropogon gerardii* Vitman) and indiangrass (*Sorghastrum nutans* L.). Forbs made up a small component of the meadow and included birdsfoot trefoil (*Lotus corniculatus* L.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), alsike clover (*Trifolium hybridum* L.) and maximilian sunflower (*Helianthus maximiliani* Schrad.).

Grazing treatments

Grazing treatments were arranged in randomized complete block design with four replicate blocks. Each block included four treatment combinations of two grazing times (pre-freeze or post-freeze) and two grazing intensities (heavy or moderate), along with a control that was ungrazed throughout the study. Pre-freeze grazing for study year one occurred from 3-12 October 2018 while grazing for study year two occurred from 7-15 October 2019. During October of both years, light frost had occurred prior to grazing but cool-season graminoids on the meadow were still green and growing. Post-freeze grazing for study year one occurred 7-15 January 2019, while that for study year two occurred from 9-17 December 2019. Meadow vegetation appeared to be dormant during the post-freeze grazing periods.

Grazing intensities of plots were achieved through a combination of plot size adjustments and visual observations. It was our goal to have approximately ≥ 75% and 50% utilization of forage (grazed and trampled/damaged) in the heavy and moderate intensity pens, respectively. In October of 2018, forage estimates were taken to arrive at initial available forage. The size of the plots was adjusted to achieve heavy or moderate grazing in approximately 48 hours. The heavy intensity plots were 0.02 hectares while moderate intensity plots were 0.04 hectares. Two mature cows (average weight ~ 567 kg) grazed each plot. Cattle were moved based on estimated consumption by the cattle (11.3 kg·day^{-1}) and visual observations of the plots. Cattle were provided free access to water.

Vegetation Sampling

Prior to and immediately following grazing of the pre-freeze and post-freeze grazing treatments, aboveground biomass in four randomly placed 0.25m^2 quadrats was clipped to ground level and gathered in paper bags. Post-grazing biomass was sorted into standing biomass and trampled/damaged biomass. Standing biomass included all vegetation that was standing at an angle of $\geq$ 45° from soil surface and that did not appear to be trampled. Trampled/damaged biomass was defined as vegetation standing at $\leq$ 45° from soil surface with clear signs of being stepped on or fouled on by cattle. Standing biomass was oven dried at 60°C to a constant weight and weighed. Differences in the dry weight of standing biomass prior to and after grazing of plots represented grazing intensity (percentage utilized).

The effects of the fall and winter grazing on the subsequent year's summer biomass were determined by clipping estimates on 8 July 2019 and 30 June 2020. The late-June to early-July period corresponded to a majority of hay harvest in the region. Four randomly placed 0.25m^2 quadrats were placed in each plot and vegetation was clipped at ground level. Samples were sorted into current year's growth of graminoids (grasses, sedges and rushes), forbs, along with dead plant material (standing dead and litter) from the previous year. Standing dead included dead plant material produced from the previous year that remained upright in current year's growth. Litter included all dead plant material that was on the soil surface. Vegetation was gathered into marked paper bags, oven dried at 60°C to a constant weight, weighed, and recorded. An additional total live weight was recorded by combining weight of graminoids and forbs in each plot.

Prior to grazing of the pre-freeze and post-freeze grazing treatment plots, forage samples were collected from esophageal fistula cows to determine quality estimates for the respective pre-freeze and post-freeze grazing periods. Cows were kept off feed for approximately 12 hours the night prior to the initiation of either the pre-freeze or the post-freeze grazing period. On the next day, the cows were haltered and allowed to graze the plots until an adequate sample was collected in catch bags. Fistula samples were then freeze-dried until all moisture was removed. In addition, forage quality was analyzed on a subset of summer biomass clippings to determine if treatments influenced subsequent year's quality. After dry weight of summer biomass was recorded, graminoids and forbs were combined and a subset of this sample was used for quality analysis. Quality of only the current year's growth was assessed to avoid the influence of dead plant material on quality. All forage quality samples were ground through a 1 mm screen and sent to Ward Labs (Kearney, Nebraska) for quality analysis. The samples were analyzed for crude protein (CP), acid detergent fiber (ADF), and total digestible nutrients (TDN) using a wet chemistry analysis.

Statistical analysis

All data were analyzed using the PROC GLIMMIX procedure in SAS 9.4 (Cary, North Carolina, USA). Forage biomass and quality during the pre-freeze and post-freeze grazing period were analyzed separately from summer biomass and quality data. To determine season trends in forage biomass and quality during the pre-freeze and post-freeze grazing periods a repeated measures model was used to estimate main fixed effects of grazing time and grazing intensity along with grazing time by grazing intensity interaction. Analysis of variance for pre-freeze and post-freeze variables was conducted for standing biomass before grazing, standing biomass after grazing, utilization, and forage quality measures (CP, ADF, and TDN). The effects of pre-freeze and post-freeze grazing on the subsequent summer biomass and quality was analyzed as a repeated measures model with a factorial plus a control treatment structure. Analysis of variance of summer biomass of each plant component (graminoid, forb, total live and dead plant material) and summer quality measurement (CP, ADF, and TDN) was conducted. Fixed effects for summer biomass and quality included in the model were grazing time, grazing intensity, year and all interactions. Blocking variability for all measurement periods (pre-freeze, post-freeze, and summer variables) was also accounted for in the model as a repeated measures term. The repeated measures term takes into account any correlation that exists between measurements that are recorded from the same plots over the two years. Data normality and variance assumptions were checked using residual plots. Treatment variables and interactions were considered significant at $P \leq 0.05$, while tests with P-values between 0.05 and 0.10 were considered trending significant. The least square mean values were estimated using the LSMEANS option in SAS.

Results

Weather

The first freeze with temperatures ≤ 0°C occurred in study year 2018/2019 on 3 October 2018 and 9 October 2019 for study year 2019/2020. Thereafter, freezes were frequent throughout the month of October. Precipitation during May-July in 2019 was

33.6 mm above the long term mean while precipitation for May-July in 2020 was 14.7 mm below the mean.

Vegetation measures of pre-freeze and post-freeze grazing periods

Standing biomass immediately before grazing during the pre-freeze period was 28.1% higher than that available during the post-freeze period ($P \leq 0.01$; Table 3.1). During both pre-freeze and post-freeze periods, similar amounts of initial standing biomass were found between heavy and moderate intensity plots ($P = 0.69$; Table 3.1). Immediately following grazing, residual standing biomass was 35.0% greater during the pre-freeze period than the post-freeze period ($P = 0.01$; Table 3.1). Standing biomass following grazing was 28.5% lower in heavy intensity plots compared to moderate intensity plots ($P = 0.04$; Table 3.1). Grazing utilization in heavy intensity plots averaged 70.8 ± 3.7% while utilization of moderate intensity plots averaged 58.8 ± 3.7% (Table 3.1).

Forage quality of the pre-freeze period was significantly greater than that of the post-freeze period (CP, ADF, TDN; $P < 0.01$; Table 3.1). Crude protein concentration of forage from the pre-freeze grazing period was 4.9 percentage units higher than that of forage CP during the post-freeze grazing period (Table 3.1). Forage of the pre-freeze grazed period was 9.2 percentage units higher in TDN and 8.1 percentage units lower in ADF compared to forage of the post-freeze period (Table 3.1).

Subsequent year biomass

There were no two-way or three-way interactions between grazing time, grazing intensity, or year that occurred on subsequent year biomass of graminoids, total live, and dead plant material. The main effect of grazing time (pre-freeze or post-freeze) had a significant effect on the subsequent year's biomass for graminoids ($P = 0.02$) and dead plant material ($P = 0.03$), with a trending effect on total live ($P = 0.09$; Fig. 3.1). When compared to post-freeze grazing, pre-freeze grazing had 13.5% less graminoid biomass (Fig. 3.1). Ungrazed control treatments produced graminoid biomass that was 11.1% greater than pre-freeze ($P = 0.09$) and similar for post-freeze ($P = 0.65$) grazing treatments (Fig. 3.1). Total live biomass of post-freeze plots was 9% greater than pre-freeze treatment plots ($P = 0.09$). Total live biomass of the ungrazed control treatment was similar to biomass of the pre-freeze ($P = 0.44$) and post-freeze ($P = 0.49$) grazing treatments (Fig. 3.1). Subsequent year dead plant material biomass in the ungrazed control was 59% and 71% greater than the dead biomass in either the pre-freeze or the post-freeze grazing treatments, respectively (Fig. 3.1).

In our study, heavy and moderate grazing did not influence graminoid ($P = 0.73$) or total live ($P =0.56$) biomass the subsequent year. Subsequent year total live plant biomass in the heavy intensity, moderate intensity, and ungrazed control treatments, averaged across grazing intensities and years was 4,697 ± 216 $\text{kg}\cdot\text{ha}^{-1}$, 4,842 ± 216 $\text{kg}\cdot\text{ha}^{-1}$, and 4,782 ± 276 $\text{kg}\cdot\text{ha}^{-1}$, respectively. Grazing intensity did influence the amount of subsequent year dead biomass collected during the harvest period in early summer ($P < 0.01$; Fig. 3.2). When compared to the ungrazed control, heavy and moderate grazing reduced dead plant material by 74.6% and 55.6%, respectively. In addition, heavy intensity plots had 42.9% less dead biomass than moderate intensity plots ($P < 0.01$).

There was significant variability between years for summer biomass estimates of graminoids, live, and dead biomass ($P < 0.01$). Summer biomass production in 2019 of graminoids and total live was 1,127 and 1,209 ± 154 $\text{kg}\cdot\text{ha}^{-1}$ more than summer biomass of 2020 for the respective plant groups. Dead biomass production was 290 ± 154 $kg \cdot ha^{-1}$ more in 2020 than 2019.

A three-way interaction of grazing time, grazing intensity, and year was observed for summer forb biomass ($P < 0.01$), however no discernable pattern emerged from this interaction (Fig. 3.3). Additionally, a grazing time main effect for forbs did exist ($P = 0.03$; Fig. 3.1). Pre-freeze grazing led to increase of forb biomass of 34% and 51% compared to the post-freeze or ungrazed control treatments, respectively.

Subsequent year forage quality

Summer crude protein was influenced by both grazing time ($P = 0.02$) and year ($P < 0.01$) main effects while TDN and ADF were only influenced by grazing time ($P < 0.01$). Grazing pre-freeze led to significantly higher crude protein in the subsequent year's plant material than either post-freeze grazing or the ungrazed control (Fig. 3.4). Crude protein in 2020 was about 0.9 percentage units higher than crude protein in 2019. Total digestible nutrients of pre-freeze grazed treatments were about 2 percentage units higher than either the post-freeze grazed or ungrazed control treatments (Fig. 3.5). In conjunction with improved TDN, ADF of pre-freeze grazed plots were about 1.8 percentage units lower than either the post-freeze or ungrazed control treatment plots (Fig. 3.5).

Discussion

Biomass

On meadows in the Sandhills, cooler temperatures and increasing precipitation provides ideal conditions for regrowth of cool-season species following summer haying. Availability of high-quality regrowth at a time when productivity and quality of upland range is declining makes meadows an attractive grazing option in the fall. Yet, grazing before the onset of a hard frost (pre-freeze grazing) significantly decreased subsequent year's production of graminoids in our study compared to delaying grazing after meadow vegetation was dormant (post-freeze grazing). There was a trending difference in graminoid biomass between pre-freeze and ungrazed control treatments. Pre-freeze graze treatments had greater forb biomass than other treatments. Total live biomass of ungrazed controls was intermediate and statistically similar to biomass of the post-freeze and pre-freeze treatments. Total live biomass of post-freeze treatments was trending on being significantly higher than biomass of pre-freeze treatments.

Forage measurements during the pre-freeze and post-freeze period indicate that forage quantity and quality decreased as the season progressed from fall to winter. Similarly, Volesky et al. (2008) saw declines in forage quality and quantity from November to February on cool-season grass irrigated plots in north central Nebraska. Across grass species in this study, standing stockpiled forage decline from 18-24%, while the range of CP loss was 25-56 $g \cdot kg^{-1}$ from November to February. Following freezing temperatures, leaching of nutrients and moisture from plant cells occur, increasing leaf brittleness and loss, resulting in declines in quantity and quality during plant dormancy (Ocumpaugh and Matches, 1977).

Lower production in fall grazed compared to winter grazed plots, leads us to believe that defoliation during fall may be damaging to future productively of meadow vegetation. Similar results were found on a white clover/grass sward in Sweden (Frankow-Lindberg et al. 1997). In this study, defoliation of regrowth prior to freezing in September resulted in lower summer production than defoliation that occurred after several killing freezes. In Wisconsin, following October defoliation of cool-season grasses, spring production was decreased but by summer, production was similar to that of December and March defoliated treatments (Riesterer et al. 2000). Fall is likely not an optimal time to graze subirrigated meadows in the Sandhills and has a negative impact on future stand production.

In our study, reductions in biomass following pre-freeze grazing may have been the result of the meadow vegetation having lower carbohydrate reserves going into winter. When defoliated in the fall, plants have limited time to replenish carbohydrate reserves before decreasing temperatures and photoperiods transition plants into dormancy. As an example, following defoliation of perennial ryegrass (*Lolium perenne* L.), a reduction of water-soluble carbohydrates (WSC) in the residual stubble and leaves occurs (Lee et al. 2005; Donaghy and Fulkerson, 1997). An increase in WSC did not occur until photosynthesis was increased following new leaf emergence. In the milder winters of New Zealand, rate of new emergence for perennial ryegrass averaged 16 days/new leaf (Lee et al. 2005). Given that freezes were frequent throughout October following our pre-freeze grazing period, leaf emergence of grasses may not have occurred. Meadow vegetation in pre-freeze treatments likely went into winter with limited carbohydrate reserves compared to post-freeze and ungrazed control treatments. This resulted in diminished future stand productivity.

Regardless of grazing time, subsequent year’s production of graminoid and total live biomass was similar under heavy, moderate, and ungrazed treatments. We would like to note that grazing intensity was not easily measured through visual observations. In our study, utilization of heavy intensity plots was slightly lower than expected while that of moderate intensity plots was higher than intended. Nonetheless, subsequent year production under grazing intensities utilizing ~59% or 71% of forage during the pre-freeze or post-freeze grazing periods were not different from each other or the ungrazed control. On upland Sandhill rangelands, subsequent summer production of cool-season grasses decreased with increases in October stocking rates (Mousel et al. 2011). Adequate soil moisture on subirrigated meadows may buffer against some of the effects of heavy grazing (Volesky et al. 2011), which may further explain the lack of response we observed from grazing intensity. However, additional years of data collection is warranted to see if continued annual heavy grazing during pre-freeze and post-freeze grazing periods is detrimental to future stand productivity.

Results of this study show that both grazing time and grazing intensity acted independently to influence the amount of dead biomass the subsequent summer. Significant reductions in graminoids in pre-freeze grazed treatments likely resulted in this treatment having the least dead biomass the following year. In addition, grazing at either heavy or moderate grazing intensities led to significantly less dead biomass by summer compared to the ungrazed control. Excessive amounts of dead biomass in tallgrass prairies can decrease soil warming in the spring, delaying plant growth and lowering stand productivity (Knapp, 1984). Additionally, dead plant material can lower forage quality when it is picked up in hay bales. Yet, reductions of dead biomass in our study did not result in increases in stand production since biomass production of ungrazed control plots was generally the same as grazed treatments. Annual haying of these meadows likely keeps dead biomass to levels that do not hinder future production. Leaving some residual dead plant material over winter does have some benefits. During winter, dead plant material insulates the growing points of plants thereby helping to protect against cold damage (Frankow-Lindberg et al. 1997). Nesting survival of greater prairie chickens (*Tympanuchus cupido pinnatus*) also increases when some standing dead residual (<25%) exists in grasslands (Matthews et al. 2013).

Forbs were influenced by a three-way interaction of grazing time, grazing intensity and year. Given the high variability that existed across grazing time, grazing intensity, and year no discernable trend could be drawn about their interacting effect. Further inspection of the grazing time main effect revealed that pre-freeze grazing significantly increased forb biomass relative to post-freeze grazing and the ungrazed control. Grazing during the pre-freeze period significantly lowered graminoid production, potentially allowing forbs increased access to light and other resources. Defoliation during the fall has been shown to increase light availability for white clover, helping to increase growing point numbers for the plants (Belesky et al. 1992). *Trifolium* species, including white clover, were the main forb species observed at our study site. Maintaining some degree of forb in the plant community is important for grassland diversity and beneficial to grassland birds (Matthews et al. 2013).

Forage Quality

Grazing before complete dormancy (pre-freeze grazing) of meadow vegetation resulted in higher forage quality than post-freeze or ungrazed control plots the subsequent summer. Pre-freeze grazing improved all measured forage quality variables (CP, ADF, and TDN). Post-freeze and ungrazed control treatments had similar forage quality measures of CP, ADF, and TDN the subsequent summer. As discussed previously, grazing pre-freeze was particularly detrimental to the subsequent year's summer graminoid production. Diminished carbohydrate reserves may have delayed growth during the following growing season, resulting in plants that were younger than plants that were grazed during dormancy or left ungrazed. While variable, generally greater forb production in the pre-freeze plots also likely contributed to greater forage quality on the pre-freeze grazed plots compared to the other treatments.

In the Nebraska Sandhills, ranching operations often face a limited availability of subirrigated meadows or upland range for winter grazing (Adams et al. 1994). Therefore, hay is the predominant feed source for cows during winter and spring (Coady and Clark, 1993). This hay-feeding period also corresponds to the late-gestation months of March calving cows, a common calving date in the Sandhills. Increased nutritional demands of late-gestation cows requires a high-quality supplemental hay feed. Pre-freeze grazing increased CP of current year's vegetation to an average value of 7.6%, slightly below the 7.9% CP requirement of a mature cow in the last third of pregnancy (Lalman and Richards, 2017). However, the averaged 59% TDN of pre-freeze grazed treatments met the requirements for not only a mature cow in the last third of pregnancy (54% TDN) but also during a cow in the first 30 days of lactation (58% TDN, Lalman and Richards, 2017). Therefore, when pregnant cows are fed summer hay from pre-freeze grazed meadows less protein supplementation may be needed compared to feeding hay from meadows that were grazed during the winter months of left ungrazed.

Management Implications

Reduced biomass but increased forage quality indicates there are tradeoffs of forage quantity and quality that occur when grazing before or after plant dormancy in the fall and winter. Graminoid biomass was reduced the subsequent summer in pre-freeze grazed treatments compared to post-freeze grazed and ungrazed treatments. Forage maturity was also likely delayed in pre-freeze grazed plots, which led to less mature though higher quality forage in this treatment. Summer hay from pre-freeze grazed meadows may have the potential to meet the nutritional demands of mature cows. Hay from either post-freeze grazed or ungrazed meadows likely would not meet these requirements and would require additional supplementation. Future research should examine the amount of carbohydrate reserves in crown and root tissues of common subirrigated meadow species following pre-freeze or post-freeze grazing.

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Tables and Figures

Table 3.1. Least square means results ± SE of time*intensity from a mixed model ANOVA for the effects of grazing time (pre-freeze, post-freeze) and grazing intensity (heavy, moderate) on respective measurements from samples collected during pre-freeze period (October 2018 & 2019) and post-freeze period (January 2019 & December 2019). Samples were collected from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

	Grazing Time (T)		Grazing Intensity (I)			P-value		
Measurement	Pre-Freeze	Post-Freeze	Heavy	Moderate	SE	T	I	T*I
Biomass before grazing[1] ($kg \cdot ha^{-1}$)	3518.6a[2]	2529.0b	2995.9	3051.7	190.0	<0.01	0.69	0.57
Biomass after grazing ($kg \cdot ha^{-1}$)	1330.3a	864.7b	915.0b	1280.0a	229.3	0.01	0.04	0.90
Utilization (%)	63.0	66.6	70.8a	58.8b	6.7	0.49	0.04	0.83
CP (%DM)[3]	13.6a	8.7b	11.1	11.3	0.4	<0.01	0.63	0.18
ADF (%DM)	31.0b	39.1a	35.5	34.6	0.9	<0.01	0.21	0.17
TDN (%DM)	67.2a	58.0b	62.1	63.1	1.0	<0.01	0.22	0.18

[1] Biomass before grazing and after grazing represents all standing biomass of the respective pre- and post-freeze grazing periods

[2] Different letters within a row represent significant differences between the means of the respective grazing time and grazing intensity main effects for each measurement at $P \leq 0.05$

[3] CP, ADF, and TDN quality measures were collected from fistulas of esophageal fistulated cows

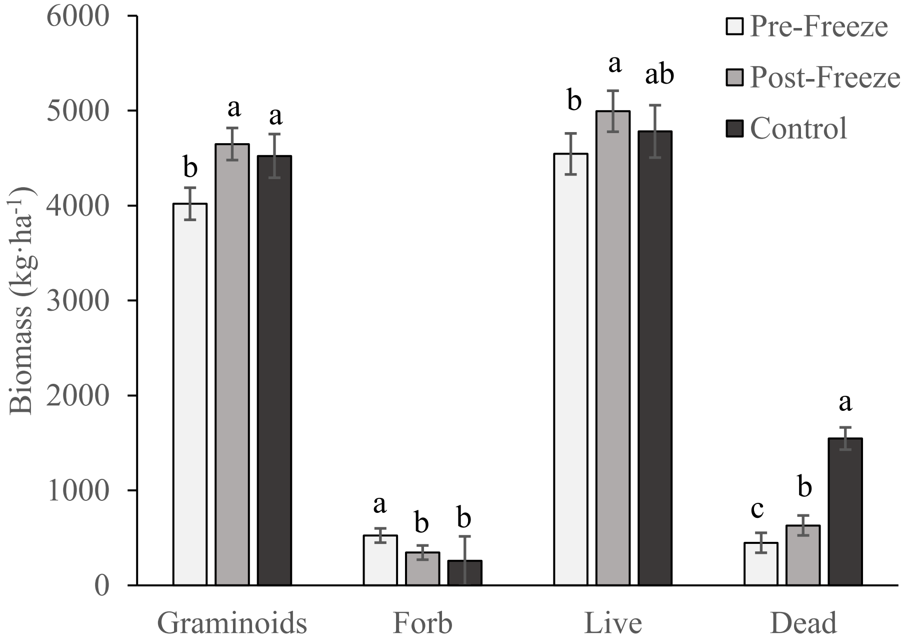

Figure 3.1. Main effect of timing of grazing on subsequent year summer biomass for the respective plant functional groups averaged across grazing intensities and years. Standard error bars are ±SE of least square means. Different letters within plant functional group indicates grazing time treatment differences at $P \leq 0.09$, based on least square means simple effects comparison method. Samples were collected in late-June and early-July from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

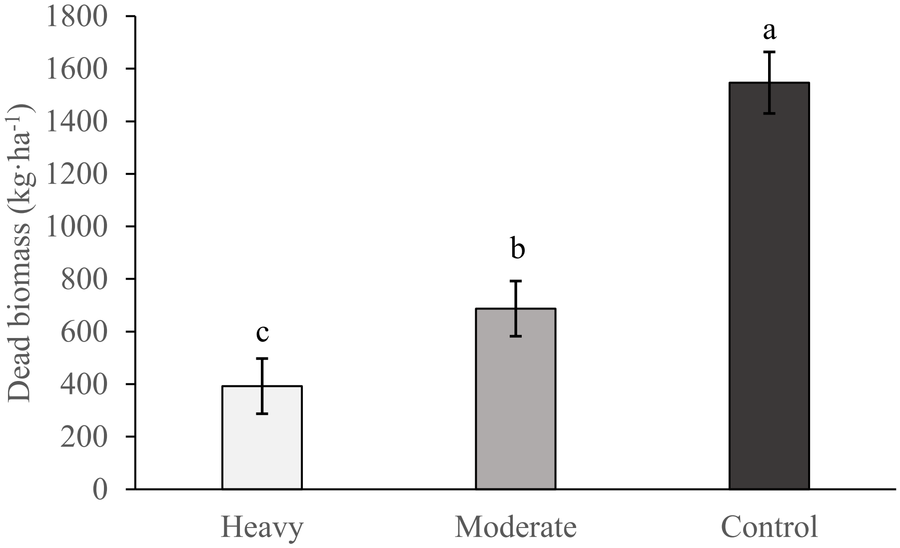

Figure 3.2. Influence of grazing intensity (heavy intensity, moderate intensity, or ungrazed controls) on the subsequent year's dead biomass. Bars represent means of the respective grazing intensities averaged across grazing times and years. Standard error bars are ±SE of least square means. Different letters across grazing intensities indicates differences at $P \leq 0.01$ based on least square means simple effects comparison method. Samples were collected in late-June and early-July from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

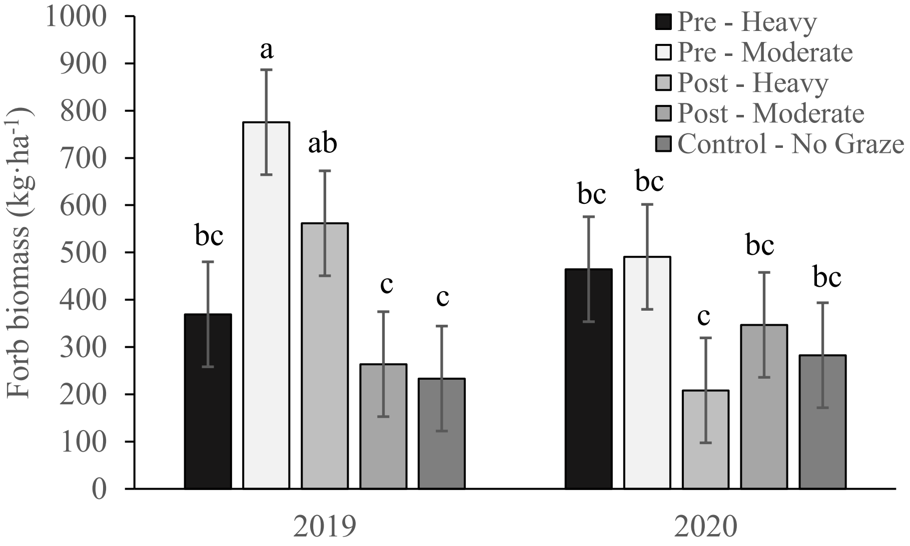

Figure 3.3. Forb three way interaction of grazing time, grazing intensity, and year. Standard error bars are ± SE of least square means. Different letters across and within years indicates differences at $P \leq 0.10$, based on least square means simple effects comparison method. Samples were collected in late-June and early-July from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

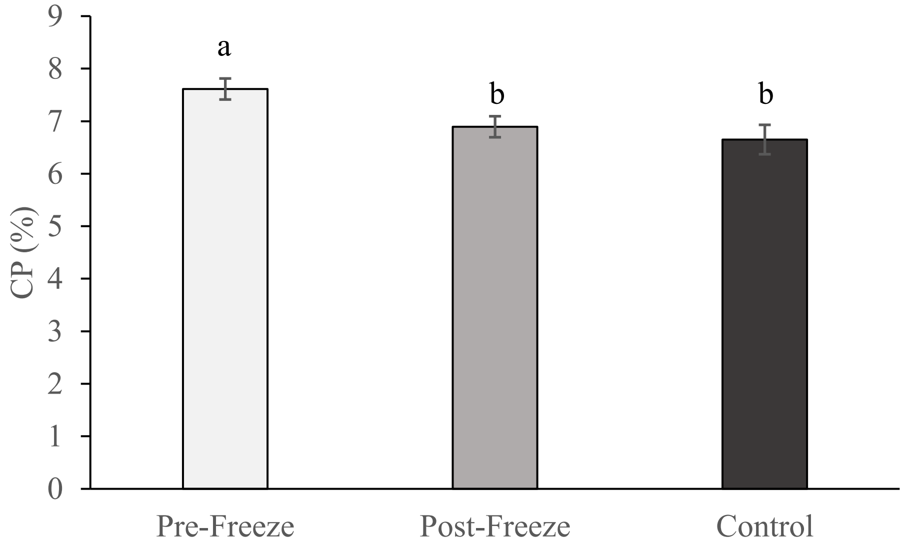

Figure 3.4. Influence of timing of grazing (pre-freeze, post-freeze, or ungrazed controls) on the subsequent year's forage crude protein. Bars represent means of the respective grazing times averaged across grazing intensities and years. Standard error bars are ±SE of least square means. Different letters across grazing times indicates time of grazing treatment differences at $P \leq 0.02$ based on least square means simple effects comparison method. Samples were collected in late-June and early-July from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.

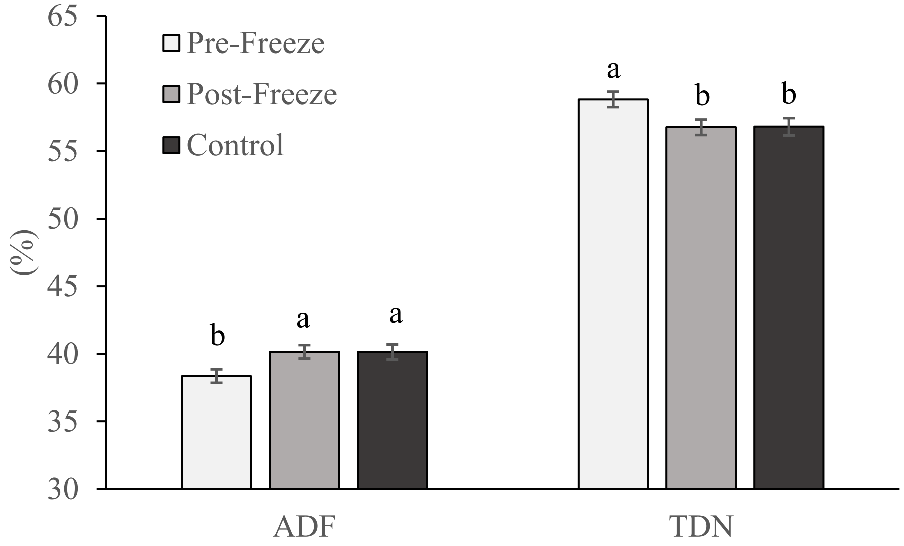

Figure 3.5. Influence of timing of grazing (pre-freeze, post-freeze, or ungrazed controls) on the subsequent year's forage quality measurements of acid detergent fiber (ADF) and total digestible nutrients (TDN). Bars represent means of the respective grazing times averaged across grazing intensities and years. Standard error bars are ±SE of least square means. Different letters within quality measurement indicates time of grazing treatment differences at $P < 0.01$ based on least square means simple effects comparison method. Samples were collected in late-June and early-July from a subirrigated meadow at the Gudmundsen Sandhills Laboratory near Whitman, Nebraska.