The Benefits of Cattle for Carbon Storage and Biodiversity in the Canadian Prairie

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by

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Overview

Over 40% of the earth's terrestrial surface is used for grazing livestock, this includes the Canadian Prairie. In addition to providing forage for animal production, these ecosystems provide a variety of other ecosystem goods and services (EG&S) critical to human welfare. While overgrazing has broadly been recognized as detrimental to EG&S, in North America the condition of rangelands has steadily been improving and fewer rangeland are overgrazed. Despite this, livestock production is still regarded as being detrimental to the health of these ecosystems and possibly limiting the amount of EG&S they provide (Eshel, Shepon, Makov, & Milo, 2014). However, many of these ecosystems, particularly grasslands, evolved with disturbance from fire or grazing by wildlife (i.e. bison) and the vegetation is adapted to these processes. Current livestock grazing practices are not identical to historical patterns of wildlife grazing but may still support the provision of EG&S by grasslands. Furthermore, many of the world's grassland have been lost through conversion to other landuses and remaining grasslands are under threat of conversion. If these ecosystems are converted, the EG&S they provide will be lost or reduced. Consequently, it is imperative that the EG&S provided by rangeland ecosystems are valued and the role of grazing in regulating them understood in order to maintain or improve their benefits for people.

The Canadian Prairies

The Canadian Prairies are a vast and diverse ecosystem that are defined by a continental climate and resulting vegetation. They cover a roughly triangular area from the southwest corner of Alberta in the foothills adjacent to the Rocky Mountains, north to Edmonton then southeast to Winnipeg. The prairies are relatively dry and most rainfall occurs through the summer, temperatures in the region are relatively hot in the summer and cold in the winter. The consequence of this climate is that trees are rare except in more northern or high-elevation locations and locally adapted grasses dominate the vegetation. These grasslands evolved with grazing by bison and other wild ungulates, bison typically grazed in the northern areas in the fall and winter, while southern areas were grazed in the summer. Finally, the soils in the region are generally rich and productive, except in the most arid regions, a result of thousands of years of plant growth.

Human activity has modified the prairie landscape. Prior to colonization by Europeans, the Prairies were home to indigenous people. Starting in the 1800s colonization of the prairies began to increase, and by the 1880s bison had largely been extirpated from the region and cattle were introduced in larger numbers. Settlement policy lead to increased numbers of homesteaders who were required to "improve" land and develop agricultural production – primarily through cultivation. The consequences of this colonization are apparent today in a vastly reduced cover of the native vegetation, which has been replaced with cropland, urban areas, and industry.

The Canadian Prairie covers an area approximately 61.5 M ha, the majority has been converted to other land uses and only 11 M ha of natural prairie remain. The loss of grassland cover varies regionally. In the northern areas, where there is the most productive soil, as much as 95% of the historical fescue grasslands have been converted to other land uses. In the south, where soils are less productive and rainfall is less reliable about 60% of the grasslands have been converted to agriculture. Of what remains, approximately 40% is public land, while the majority is privately owned and used for grazing cattle.

The primary driver of most ecosystem processes, particularly plant growth, and their ability to provide EG&S, in the Canadian Prairies is rainfall Prairie (Bork, Thomas, & McDougall, 2001; Smoliak, 1956; Smoliak, 1986), as is true of most arid grasslands in North America (O. E. Sala, Parton, Joyce, & Lauenroth, 1988). Nutrient limitation can also be a factor in the provision of EG&S in this region, but typically only when there is more than 500 mm of rainfall annually. It's important to note that not only are these systems receiving among the least amount of precipitation, but rainfall is highly variable in grasslands from one year to the next which can create large swings the amount of ecological processes and in particular, annual plant growth (Knapp & Smith, 2001; Smoliak, 1986).

Cattle in the Canadian Prairie

There are approximately 8.2 M beef cattle in the Western Canadian Provinces, 5.8 M of which are in cow-calf operations (Stats Canada, 2019), which represents a multi-billion dollar industry. While the industry is economically substantial, margins can be slight for individual producers and their largest cost is feed. Grazing on grassland is critically important as it is the least expensive feed source available to cow-calf producers and covers approximately 12 M ha in the prairies.

Cattle management is highly variable across the prairies, but a few factors have been identified as being important in determining the impacts grazing cattle have on the prairie environment. The first is stocking rate (Briske et al., 2008), a measure of the intensity of cattle use of a pasture that is simply determined as the number of animals per unit area per unit time. Stocking rate is typically expressed on the basis of AUM (animal unit months), where 1 AUM is equal to a 1000 lb. cow grazing for 1 month. Recommended stocking rates in the Canadian prairie range from 0.001 AUM/acre in very unproductive environments to 8 AUM/acre in very productive environments, although producers may stock at rates greater than that. The second most important factor affecting cattle impacts is the season of grazing. It is widely recommended that cattle not graze native grasslands in the Canadian Prairie until after the middle of July. Grazing too intensely or too early can degrade the environment through its impacts on vegetation.

Cattle have two generalized effects on vegetation, which in turn will affect EG&S. First, overgrazing can reduce the vigour of an individual plant. As cattle consume a plant's leaves, the plant must reallocate carbohydrates stored in the roots to the regrowth of new leaves. If too much leaf is repeatedly removed then the plant's below ground resources (carbohydrates stored in roots) will be depleted which can have impacts on the vegetation but also on soils, as will be discussed later. Secondly, some plants are better adapted to grazing than other plants. Over time, if grazing intensity is sufficient, plants that aren't as well adapted to grazing will be reduced in the ecosystem, or disappear entirely, while those that are tolerant of grazing will increase. Typically, the plants that increase are less desirable because they are smaller, slower growing, less productive or less nutritious. Through these effects on vegetation cattle can act to modify some EG&S as vegetation is an important driver of their provisioning.

Ecosystem goods and services

Ecosystem goods and services are the benefits that people receive from the landscape. EG&S are commonly broken down into four different categories. First, there are *provisioning services* that can include "goods" such as forage, timber, fish, fibers and other raw materials. *Regulating services*, such as pollination and climate regulation, that maintain the ecosystems in which we live and depend on. *Supporting services*, such as nutrient and water cycling. Finally, there are *cultural services* such as aesthetics, recreation and education.

Grasslands have long been recognized for the variety of ecosystem goods and services they provide (Havstad et al., 2007), but not all provide revenue or reward to landowners. While forage production for livestock is often the foremost provision from grasslands, grasslands supply a variety of other EG&S and the focus on these alternate EG&S has been increasing in recent years (Osvaldo E. Sala, Yahdjian, Havstad, & Aguiar, 2017). There is increasing focus on the regulating services provided by grasslands, in particular the storage of carbon and its role in mitigating climate change. However, while landowners receive revenue from forage production through the livestock they produce there are few incentives to encourage storage of carbon – despite an increasing number of jurisdictions globally that have placed a price on carbon.

This document is examining the effect of cattle on carbon storage and biodiversity. Carbon storage is clearly an EG&S, based on the definition above, but biodiversity is not necessarily an ecosystem service. However, biodiversity does support other EG&S and some may find aesthetic and cultural benefits based in biodiversity (Daily, 1997). There is ample research demonstrating that increases in biodiversity lead to increases in EG&S, particularly plant biomass production (Cardinale et al., 2007), which is highly relevant within the Canadian Prairie because of its direct relationship with forage and livestock production.

Effects of cattle on carbon storage

Carbon, greenhouse gases and climate change

Increased amounts of greenhouse gases (GHG) in the atmosphere are causing the earth's climate to change, and management of landscapes that leads to increased biological sequestration of carbon could reduce these impacts. While there are numerous different types of GHG the two primary ones I will consider here are carbon dioxide (CO_2) and methane (CH_4). The earth's soils store approximately 2300 Pg of carbon, approximately three times the amount in the atmosphere and nearly four times the amount in living plants and animals (Lal, 2002). Carbon dioxide is relevant because it is the most abundant greenhouse gas and is the product of biological respiration, and is consumed by plants during their growth as part of photosynthesis. Methane is the product of anaerobic respiration and can be produced by microorganisms in the soil but is most notably produced in the rumen of cattle, which is considered to be one of the primary environmental impacts of cattle. However, some microorganisms in the soil can consume methane under certain environmental conditions leading to its reduction in the atmosphere and incorporation into soil. Thus owing to the great expanse of grazed ecosystems and their capacity to store carbon in soils, small changes in grazing management that lead to increases in soil organic carbon could have potentially large impacts on the amount of GHG in the atmosphere.

Landuse effects on carbon stocks

Grasslands are currently estimated to hold 30% of global soil carbon stocks (Lal, 2002). Large amounts of carbon are lost from soils when land use changes. When grasslands are cultivated they can lose 30 – 50% of the carbon stored in the top layers of soil. This loss is the result of increased aerobic respiration by microorganisms and loss through erosion as the removal of vegetation the soils are prone to erosion by wind and water. Thus, cattle production on grasslands maintains large amounts of carbon in soils through the avoided cultivation of the land. In Alberta, experiments testing the effects of land conversion on soil carbon found that cultivated wheat fields in the dry mixedgrass prairie had 22% less soil organic carbon that native grasslands 13 years after conversion (Thomas, Hao, & Willms, 2016) and after 6 years the mixed-grass and fescue foothills had about 30% less soil carbon (Whalen, Willms, & Dormaar, 2003). Forested and non-forested pastures in the parkland of Alberta hold as much soil carbon as forest soils and more than twice as much as cropland (Baah-Acheamfour, Carlyle, Bork, & Chang, 2014). Recovery of carbon into these soils following abandonment of cultivation can take decades (Wang, VandenBygaart, & McConkey, 2014). Thus, a key strategy for preventing further increases in atmospheric GHG should be to maintain the carbon currently in grassland soils.

Effects of cattle on carbon stocks

The effects of cattle grazing on soil carbon stocks in grasslands has been extensively studied, but results of are highly variable with individual studies showing that grazing can increase, decrease or have no effect on soil carbon (J.D. Derner & G. E. Schuman, 2007; McSherry & Ritchie, 2013). More local to the Canadian prairies, a meta-analysis showed that grazing increase soil carbon (Wang et al., 2014); however, single studies, which tend to be a few locations, find varying results. Across a range of stocking rates in the foothills of Alberta, grazing had no effect (Li et al., 2012), even though a previous study at the same location reported reductions due to grazing (Dormaar & Willms, 1998). But across three other sites in Alberta, grazing increased soil carbon at lower stocking rates, while overgrazing, too early in the season, reduced soil carbon (Naeth, Bailey, Pluth, Chanasyk, & Hardin, 1991). In an attempt to reconcile these seemingly contradictory findings another study investigated 108 locations, each with and without grazing, across southern Alberta and found overall that grazing increased carbon in the upper layer of soil (Hewins et al., 2018). However, it should be noted that these sites were on provincial land and experience levels of grazing typically lower than that of private land. Appropriate grazing management can increase soil carbon. In the US carbon accumulation rates can increase by 0.1 to 0.3 Mg/ha/year (Schuman, Janzen, & Herrick, 2002) and in Canada the rates has been estimated at 0.19 Mg/ha/year (Wang et al., 2014). Furthermore, it has been suggested that grazing can increase the stability of carbon stocks, meaning that it is less likely to be respired into the atmosphere (J.D. Derner & G. E. Schuman, 2007), but a study in Alberta found no evidence of this pattern (Hewins et al., 2018). While there seems to be increasing consensus that cattle can increase soil carbon the underlying mechanisms for the increases and how they vary across different locations is less clear. These mechanisms may include: 1) increased plant root biomass, 2) increased carbon content of soil organic matter and 3) compaction of soil to have greater bulk density (Piñeiro, Paruelo, Oesterheld, & Jobbágy, 2010), but these processes require further study in order to understand how cattle improve soil carbon and generate site specific management recommendations.

Effects of cattle on GHG flux

While the ultimate measureable benefit of grasslands for storing carbon is in the amount of carbon in the soil, there is also interest and benefit in understanding how grazing affects carbon storage through other processes. GHG flux represents a movement of gases in and out of the soil. The production of carbon dioxide through respiration is a necessary biological process, and results from the growth and activity of plants, microorganisms and other soil fauna. The net accumulation of C in soils will be the result of the difference in carbon dioxide respired and carbon dioxide captured in photosynthesis. Typically, we see that moderate levels of grazing increase plant production and soil microbial activity, which leads to increases in carbon dioxide emissions from soils. However, the overall control on SOC is incredibly complex (Piñeiro et al., 2010), so despite increased emissions from soils we typically see greater soil carbon in these more productive environments. Methane is another important GHG, and as mentioned, produced anaerobically in the guts of cattle and in the soil. Grazing management that reduces soil moisture, and increases aerobic respiration can lead to increased consumption of methane by microorganisms helping to offset GHG, although this amount is very small. A recent global-meta analysis indicates that heavy grazing reduces the flux of GHG from grasslands soils, but this also resulted in degraded grasslands with reduced plant growth, soil moisture and not a desirable management state (Tang et al., 2019). Additionally, there is interest in comparing different landuses in terms of their GHG flux. Cultivated lands tend to release more nitrous oxide than grasslands, primarily because of the addition of fertilizer into these systems. In Alberta, pasture agroforestry systems had greater uptake of methane, extremely low release of nitrous oxide and lower carbon dioxide release than agroforestry cropland systems (Baah-Acheamfour, Carlyle, Lim, Bork, & Chang, 2016).

Effects of cattle grazing on biodiversity

Biodiversity is the variety of life on earth and can be assessed at the level of species, ecosystems or genes. While there may certainly be cattle grazing effects on genetic diversity here we will focus on the biodiversity at the level of species and ecosystems. Species diversity is typically measured in two ways: 1) species richness, a count of the number of species present in a given area at a given time or 2) a metric that combines species richness with an assessment of each species' relative abundance, typically called "diversity". Species level diversity is usually measured within a single taxa (e.g. plants or birds) because the spatial scale at which different taxa respond to change and that they are measured on is different. In this document, I will examine the relationship between cattle and endangered species, plants and birds, as more information is available on those taxa. Concepts and measures of multiple taxa, "multidiversity", are relatively new but will likely be more widely explored in the future. Ecosystem diversity is typically assessed as the number of different vegetation types within a given region at a particular time and can be assessed similarly to species diversity. Ecosystem diversity can be described with a number of different terms, such as "landscape heterogeneity" or "patchiness".

Biodiversity is recognized as being important because it often leads to greater overall EG&S (Gamfeldt et al. 2008); here are a few examples. Beyond increased forage production, more diverse ecosystems tend to have more stable plant production from one year to the next (Tilman & Downing 1994). Degraded grasslands recover their soil organic carbon faster when plant diversity is higher (Yang, Tilman, Furey, & Lehman, 2019). And finally, more diverse ecosystems are better at improving water quality (Cardnale 2011). Furthermore, people often assign value to biodiversity itself, which is thought to be greater when there are more species or when the biodiversity of an area represents what is considered “natural”.

Cultivated land and grasslands will clearly differ in their diversity because cultivated lands are typically managed for the production of a single plant species, but what happens at a larger spatial scale when the relative amounts of grassland and cultivated land change at regional scales is instead of interest. Habitat loss, primarily through grassland cultivation, is the leading cause of decline for virtually all extirpated, and threatened species in the Canadian Prairie (Species at Risk Public Registry, 2019) and globally cropland has had among the largest impact on biodiversity (Newbold et al. 2015). Increasing landscape heterogeneity has been recognized as a key strategy to help increase biodiversity in agricultural landscapes (Benton, Vickery, & Wilson, 2003) and cultivation removes heterogeneity while cattle appropriate cattle grazing can increase heterogeneity.

Cattle grazing and endangered species

The leading cause of decline for most listed threatened or endangered species in the Canadian Prairie is habitat loss, which is primarily due to the cultivation of native grassland for crop production (Species at Risk Public Registry). Examples of extirpated prairie species include, the grizzly bear, which was historically a species of the plains, the black-footed ferret and the prairie chicken. The loss of these species from the region directly reduces its overall biodiversity. Without a long view of history, the unfortunate perception is that because these species' remaining habitat is the same land used for grazing cattle that cattle have been responsible for their decline. An example is the Greater Sage Grouse and endangered bird living in southern Alberta and Saskatchewan and adjoining US states. Its population has declined dramatically due to land conversion, industrial disturbance and development of tame forages, and its habitat is within remaining rangeland in the region. Consequently, its remaining habitat exists because it has not been converted to other landuse and the use of these lands for cattle has likely prevented conversion. As much of this land is privately owned, conservation and research efforts should then focus on the best ways to manage grazing that enables producers to have an economically viable operation while maintaining or improving habitat and populations of endangered species, and ensuring that these lands are not converted to other landuses.

Cattle grazing and plant diversity

The relationship between grazing and plant diversity is well studied and the patterns are substantially supported by empirical observation and theoretical understanding. The common pattern is referred to the “intermediate disturbance hypothesis”, which suggests that plant diversity is greatest at intermediate levels of grazing intensity (Connell, 1978; Grime, 1973). This model has been further built upon to incorporate climate differences between different regions and that some areas, especially those in the Canadian prairie, evolved with grazing and are likely more resistant to the effects of grazing (Milchunas, Sala, & Lauenroth, 1988). When grazing intensity is too low, a single plant species often dominates the landscape and competitively excludes other species. When grazing intensity is too high, there a few plant species that can tolerate that amount of disturbance and few species exist. However, at intermediate levels of disturbance there is a trade off between these processes leading to maximum numbers of species. The pattern of the intermediate disturbance hypothesis has been seen in the Canadian prairie in relation to rangeland condition (Bai, Abouguendia, & Redmann, 2001) and moderate grazing increases plant diversity above that of ungrazed areas (Lyseng et al., 2018) – both studies demonstrate that some grazing is required to achieve higher plant diversity. An additional process also occurs at intermediate levels of grazing, cattle grazing behavior leads to the creation of patches, which increases landscape heterogeneity and increases species diversity at a larger scale (Milchunas et al., 1988; Adler, Raff, & Lauenroth, 2001; McGranahan, Hovick, Elmore, Engle, & Fuhlendorf, 2018). Although, it should be noted that overgrazing can homogenize landscape leading to reduced landscape heterogeneity (Kéfi et al., 2007).

Cattle grazing and bird diversity

One third of North American bird species require urgent conservation and grassland birds have experienced among the greatest declines in abundance of all types of birds and so efforts to conserve these species have received much attention. Habitat loss is the leading cause of their decline, but the question remains as to the effects of cattle on birds and how grazing management might be improved to the benefit of these species. Cattle can have a variety of effects on birds. First, they can directly negatively affect birds through actions such as the trampling of nests (Churchwell, Davis, Craig A., Fuhlendorf, S.D., & Engle). Secondly, grazing can cause indirect effects such as changes in vegetation used as habitat or the availability of food to either the benefit or detriment of birds, but these effects tend to be specific to particular bird species (Fuhlendorf et al., 2006).

Cattle grazing and the diversity of other taxa

The effects of cattle on other taxa have been investigated, but the patterns are often complex and the mechanisms underlying them poorly understood because they have not been studied to the same extent as plants and birds. For example, grazing increased ant diversity in productive grasslands but reduced their diversity in low productivity grasslands in BC (Amanda C. Schmidt, Lauchlan H. Fraser, Cameron N. Carlyle, & Eleanor R. L. Bassett, 2012); little is known about the ecology of each species of ant in order to understand their response or the consequence of these changes. Ongoing work examining bee diversity in response to grazing suggests that the maintenance of litter in these systems is very important but, again, the response is highly specific to individual bee species (Carlyle, unpublished data). Advances in basic ecological knowledge of species living within the Canadian prairie will help to develop conservation efforts for the species, the benefits they may be providing to the landscape and aid in developing cattle management strategies that benefit more species.

Ongoing research

Within Alberta there are currently a number of recently completed and on-going projects that will help to refine our understanding of the effects of grazing on both carbon and biodiversity. I mention these here, as they will be relevant to defining the role of Canadian Prairies in supporting EG&S in Canada, the development of policy to support grassland stewardship and conservation, the management of these systems by producers and perception of the beef industry by the general public. The author (Carlyle) is involved with all of these projects and can be contacted for further information:

- Effect of stocking rate and grazing systems on soil carbon and GHG across the Canadian Prairies
- Effect of grazing exclusion on GHG and soil microbial processes in Alberta
- Effect of stocking rates on biodiversity in Alberta
- Effect of rangeland health on plant diversity at multiple spatial scales in Alberta
- Effects of grazing exclusion on plant community structure and invasive species
- Effect of drought and grazing systems on vegetation, soil carbon, and GHG in Alberta
- Effect of grazing and land-use on native bees in Alberta

Future research needs

Much of the current research on the effects of cattle on EG&S is focused on the bio-physical aspects of this relationship, and while there is much to be learned on that front additional research that will advance the development and adoption of policy to support grassland stewardship, incentives for providing EG&S and public recognition of the EG&S supported by healthy rangelands is needed. As highlighted, native grassland ecosystems provide carbon storage and biodiversity, but are being converted to cultivated lands, which have less carbon and biodiversity value. In Alberta, the rate of conversion is lower than other jurisdictions in North America, but climate change is predicted to increase the suitability of land in the Canadian Prairie for crops. Research is needed to determine the appropriate type and level of incentives to avoid conversion. Furthermore, managing for carbon and biodiversity may be at odds with each other and are likely not optimized under the same management regime. For example, widespread adoption of management practices that increase soil carbon could lead to homogenization of the landscape and reduce biodiversity. It is critical that unintended consequences of policy be avoided though an implementation process that considers possible side effects on the entire ecosystem, not just the particular EG&S of interest. Increasing carbon and biodiversity, along with other EG&S, may not always require the same management strategy and may require tradeoffs that producers will need to be informed on. Finally, some EG&S such as biodiversity and water regulation are controlled by processes that happen at very large scales and the question arises as to how to coordinate their management across multiple landowners. Ultimately, for the benefit of all people within the Canadian Prairie, future research needs to support the development of policy that promotes cattle management that increases EG&S while supporting the private landowners who steward millions of acres of native grasslands.

Summary

Cattle and beef production have gained a negative opinion by some segments of the general public. However, past research done within the Canadian Prairie and in other regions have demonstrated that with appropriate management, cattle on native grasslands can increase some of the EG&S that we value. The cattle industry through the maintenance of large areas of native grasslands, rather than crop production, support wildlife habitat and avoid the loss of carbon that occurs with cultivation. Many studies highlight that moderate levels of grazing maintain biodiversity and soil carbon at levels above what these systems provide when grazing is removed, and especially above the level provided by other land uses, such as cultivation. Currently though, with few exceptions, the primary revenue from grasslands is by beef production. Conservation of these lands through policy that provides incentives to landowners to continue grazing these lands at moderate rates, rather than alternate land-uses, is key to the long-term maintenance of EG&S and human well-being.

References

Adler, P., Raff, D., & Lauenroth, W. (2001). The effect of grazing on the spatial heterogeneity of vegetation. *Oecologia, 128*(4), 465-479. doi:10.1007/s004420100737

Amanda C. Schmidt, Lauchlan H. Fraser, Cameron N. Carlyle, & Eleanor R. L. Bassett. (2012). Does cattle grazing affect ant abundance and diversity in temperate grasslands? *Rangeland Ecology & Management, 65*(3), 292-298. doi:10.2111/REM-D-11-00100.1

Baah-Acheamfour, M., Carlyle, C. N., Bork, E. W., & Chang, S. X. (2014). Trees increase soil carbon and its stability in three agroforestry systems in central alberta, canada. *Forest Ecology and Management, 328*, 131-139. doi:10.1016/j.foreco.2014.05.031

Baah-Acheamfour, M., Carlyle, C. N., Lim, S. -., Bork, E. W., & Chang, S. X. (2016). Forest and grassland cover types reduce net greenhouse gas emissions from agricultural soils. *Science of the Total Environment, 571*, 1115-1127. doi:10.1016/j.scitotenv.2016.07.106

Bai, Y., Abouguendia, Z., & Redmann, R. E. (2001). Relationship between plant species diversity and grassland condition. *Journal of Range Management, 54*(2), 177-183. doi:10.2307/4003180

Benton, T. G., Vickery, J. A., & Wilson, J. D. (2003). *Farmland biodiversity: Is habitat heterogeneity the key?* doi://doi-org.login.ezproxy.library.ualberta.ca/10.1016/S0169-5347(03)00011-9

Bork, E. W., Thomas, T., & McDougall, B. (2001). Herbage response to precipitation in central alberta boreal grasslands. *Journal of Range Management, 54*(3), 243-248. doi:10.2307/4003241

Briske, D. D., Derner, J. D., Brown, J. R., Fuhlendorf, S. D., Teague, W. R., Havstad, K. M., . . . Willms, W. D. (2008). Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. *Rangeland Ecology and Management, 61*(1), 3-17. doi:10.2111/06-159R.1

Cardinale, B. J., Wright, J. P., Cadotte, M. W., Carroll, I. T., Hector, A., Srivastava, D. S., . . . Weis, J. J. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences, 104*(46), 18123-18128.

Churchwell, R., Davis, Craig A., Fuhlendorf, S.D., & Engle, D. M.Direct impacts of cattle grazing on grassland nesting birds. *Bulletin of the Oklahoma Ornithological Society, 38*, 25-30.

Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs. *Science, 199*(4335), 1302-1310. doi:10.1126/science.199.4335.1302

Daily, G. C. (1997). *Nature's services: Societal dependence on natural ecosystems*. Washington, DC: Island Press.

Dormaar, J. F., & Willms, W. D. (1998). Effect of forty-four years of grazing on fescue grassland soils. *Journal of Range Management, 51*(1), 122-126. doi:10.2307/4003574

Eshel, G., Shepon, A., Makov, T., & Milo, R. (2014). Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the united states. *Proceedings of the National Academy of Sciences, 111*(33), 11996-12001.

Fuhlendorf, S. D., Harrell, W. C., Engle, D. M., Hamilton, R. G., Davis, C. A., & Leslie Jr., D. M. (2006). Should heterogeneity be the basis for conservation? grassland bird response to fire and grazing. *Ecological Applications, 16*(5), 1706-1716.

Gamfeldt, L., Hillebrand, H., & Jonsson, P. R. (2008). Multiple functions increase the importance of biodiversity for overall ecosystem functioning. *Ecology, 89*(5), 1223-1231. doi:10.1890/06-2091.1

Grime, J. P. (1973). Competitive exclusion in herbaceous vegetation. *Nature, 242*(5396), 344-347. doi:10.1038/242344a0

Havstad, K. M., Peters, D. P. C., Skaggs, R., Brown, J., Bestelmeyer, B., Fredrickson, E., . . . Wright, J. (2007). Ecological services to and from rangelands of the united states. *Ecological Economics, 64*(2), 261-268. doi:10.1016/j.ecolecon.2007.08.005

Hewins, D. B., Lyseng, M. P., Schoderbek, D. F., Alexander, M., Willms, W. D., Carlyle, C. N., . . . Bork, E. W. (2018). Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. *Scientific Reports, 8*(1), 1336-9. doi:10.1038/s41598-018-19785-1

J.D. Derner, & G. E. Schuman. (2007). Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation, 62*(2), 77. Retrieved from http://www.jswconline.org/content/62/2/77.abstract

Kéfi, S., Rietkerk, M., Alados, C. L., Pueyo, Y., Papanastasis, V. P., ElAich, A., et al. (2007). Spatial vegetation patterns and imminent desertification in mediterranean arid ecosystems. *Nature, 449*, 213. Retrieved from https://doi.org/10.1038/nature06111

Knapp, A. K., & Smith, M. D. (2001). Variation among biomes in temporal dynamics of aboveground primary production. *Science, 291*(5503), 481-484. doi:10.1126/science.291.5503.481

Lal, R. (2002). Soil carbon dynamics in cropland and rangeland. *Environmental Pollution, 116*(3), 353-362. doi:10.1016/S0269-7491(01)00211-1

Li, C., Hao, X., Ellert, B. H., Willms, W. D., Zhao, M., & Han, G. (2012). Changes in soil C, N, and P with long-term (58 years) cattle grazing on rough fescue grassland. *Journal of Plant Nutrition and Soil Science, 175*(3), 339-344. doi:10.1002/jpln.201100212

Lyseng, M. P., Bork, E. W., Hewins, D. B., Alexander, M. J., Carlyle, C. N., Chang, S. X., & Willms, W. D. (2018). Long-term grazing impacts on vegetation diversity, composition, and exotic species presence across an aridity gradient in northern temperate grasslands. *Plant Ecology, 219*(6), 649-663. doi:10.1007/s11258-018-0824-4

McGranahan, D. A., Hovick, T. J., Elmore, R. D., Engle, D. M., & Fuhlendorf, S. D. (2018). Moderate patchiness optimizes heterogeneity, stability, and beta diversity in mesic grassland. *Ecology and Evolution, 8*(10), 5008-5015. doi:10.1002/ece3.4081

McSherry, M. E., & Ritchie, M. E. (2013). Effects of grazing on grassland soil carbon: A global review. *Global Change Biology, 19*(5), 1347-1357. doi:10.1111/gcb.12144

Milchunas, D. G., Sala, O. E., & Lauenroth, W. K. (1988). A generalized model of the effects of grazing by large herbivores on grassland community structure. *The American Naturalist, 132*(1), 87-106. doi:10.1086/284839

Naeth, M. A., Bailey, A. W., Pluth, D. J., Chanasyk, D. S., & Hardin, R. T. (1991). Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of alberta. *Journal of Range Management, 44*(1), 7-12. doi:10.2307/4002629

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature, 520*(7545), 45-50. doi:10.1038/nature14324

Piñeiro, G., Paruelo, J. M., Oesterheld, M., & Jobbágy, E. G. (2010). Pathways of grazing effects on soil organic carbon and nitrogen. *Rangeland Ecology & Management, 63*(1), 109-119. doi:10.2111/08-255.1

Sala, O. E., Parton, W. J., Joyce, L. A., & Lauenroth, W. K. (1988). Primary production of the central grassland region of the united states. *Ecology, 69*(1), 40-45. doi:10.2307/1943158

Sala, O. E., Yahdjian, L., Havstad, K., & Aguiar, M. R. (2017). Rangeland ecosystem services: Nature’s supply and humans’ demand. In D. D. Briske (Ed.), *Rangeland systems: Processes, management and challenges* (pp. 467-489). Cham: Springer International Publishing. doi:10.1007/978-3-319-46709-2_14 Retrieved from https://doi.org/10.1007/978-3-319-46709-2_14

Schuman, G. E., Janzen, H. H., & Herrick, J. E. (2002). Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution, 116*(3), 391-396. doi:10.1016/S0269-7491(01)00215-9

Smoliak, S. (1956). Influence of climatic conditions on forage production of shortgrass rangeland. *Journal of Range Management, 9*(2), 89-91. doi:10.2307/3894557

Smoliak, S. (1986). Influence of climatic conditions on production of stipa-bouteloua prairie over a 50-year period. *Journal of Range Management, 39*(2), 100-103. doi:10.2307/3899276

Species at Risk Registry. (2019) Accessed March 2019. https://wildlife-species.canada.ca/species-risk-registry/sar/index/default_e.cfm

Tang, S., Wang, K., Xiang, Y., Tian, D., Wang, J., Liu, Y., . . . Niu, S. (2019). Heavy grazing reduces grassland soil greenhouse gas fluxes: A global meta-analysis. *Science of the Total Environment, 654*, 1218-1224. doi:10.1016/j.scitotenv.2018.11.082

Thomas, B. W., Hao, X., & Willms, W. D. (2016). Soil organic carbon, nitrogen, and phosphorus 13 yr after abruptly disturbing northern great plains grassland. *Canadian Journal of Soil Science, 97*(2), 329-333. doi:10.1139/cjss-2016-0113

Tilman, D., & Downing, J. A. (1994). Biodiversity and stability in grasslands. *Nature, 367*(6461), 363-365. doi:10.1038/367363a0

Wang, X., VandenBygaart, A. J., & McConkey, B. C. (2014). Land management history of canadian grasslands and the impact on soil carbon storage. *Rangeland Ecology & Management, 67*(4), 333-343. doi:10.2111/REM-D-14-00006.1

Whalen, J. K., Willms, W. D., & Dormaar, J. F. (2003). Soil carbon, nitrogen and phosphorus in modified rangeland communities. *Journal of Range Management, 56*(6), 665-672. doi:10.2307/4003944

Yang, Y., Tilman, D., Furey, G., & Lehman, C. (2019). Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications, 10*(1), 718. doi:10.1038/s41467-019-08636-w