TESTING INTENSIVE CATTLE GRAZING MANAGEMENT AS A RESTORATION TOOL IN INVADED, SEMI-ARID GRASSLANDS

by

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ABSTRACT

Overgrazing and invasive species pose significant threats to the livelihood of British Columbia (B.C.) ranchers. Spotted knapweed (*Centaurea stoebe*), in particular, can reduce native plant diversity, form dense monocultures and overwhelm the native seed bank. Integrated land management strategies are therefore needed to suppress weeds and restore ecological function as a whole. Recent research suggests that short-duration, light to moderate grazing may aid in restoring grasslands. My primary research objective was to test management-intensive grazing (MiG), extensive grazing, and targeted cattle grazing for their effects on: a) plant community structure and productivity, b) soil chemical and physical properties, and c) the storage of soil carbon in a semi-arid grassland. A secondary objective was to determine the efficacy of targeted cattle grazing to suppress *C. stoebe* seed production. Electric fence enclosures were established in *C. stoebe* dominated grassland in Merritt, BC. Cattle numbers and timing were controlled such that MiG was ten cow/calf pairs for one day at the end of the summer growing season, extensive was one cow/calf pair for ten days at the end of the summer growing season and targeted was ten cow/calf pairs for one day at the height of spotted knapweed flowering. Results demonstrated that MiG improved native grass cover and productivity, but total productivity, diversity indices or soil properties did not differ from extensive grazing. Targeted cattle grazing was effective in controlling *C. stoebe* seed production; cattle readily consumed *C. stoebe* at the late bud-flowering stage and reduced the number of mature seeds by 88% and seed heads by 79%. At the point of targeted grazing, *C. stoebe* also contained more crude protein and total digestible nutrients than the grass community. This research helped demonstrate that intensive grazing practices have the potential to create productive invasive-free grasslands in B.C.'s southern interior and beyond. Research results generated recommendations for implementing MiG on natural semi-arid grasslands, as well as for targeted cattle grazing for *C. stoebe* control.

Key words: Grasslands, spotted knapweed, management-intensive grazing, soil carbon sequestration, targeted grazing, forage quality, soil seed bank, biodiversity

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1. CHAPTER 1

INTRODUCTION: GRASSLANDS AND RESTORATION

Grasslands and Their Importance

Grasslands historically covered 61.5 million hectares of Canadian soil (Clayton et al. 1977), however, only 11.4 million hectares remain today (Alemu et al. 2019). In the Canadian prairie provinces, including Alberta, Saskatchewan, and Manitoba, much of the native grasslands have been transformed into cultivated cropland or hay fields (Vankosky et al. 2017). However, in British Columbia (B.C.), approximately 1% of the native grasslands remain intact (Iverson 2004) and play important cultural, societal, environmental, and economic roles.

Indigenous communities have made use of the grassland's abundant flora for food, medicinal, and ceremonial purposes for time immemorial (Blackstock and McAllister 2004). Land users explore and recreate in grasslands for their unique landform features and aesthetics. Endangered wildlife species spend either a portion or the entirety of their lifecycles within grasslands (Gayton 2003). Furthermore, organic matter incorporates into the soil through the annual shedding and decomposition of plant roots; thus, grasslands also assist in the mitigation of climate change through the uptake and long-term storage of atmospheric carbon (Gayton 2003; Harrower et al. 2012; Lloyd 2019).

Grasslands are also an important resource for cattle ranching in B.C., an industry estimated to contribute $600 million to the economy annually (BCCA 2020). Grasslands used for forage and livestock production are termed 'rangelands' (Lund 2007), where approximately 80% of B.C.'s cattle operations utilize crown - or provincially administered – rangeland (BCCA 2020). Despite forested areas composing 80% of the crown range in B.C. (Wikeem et al. 1993), a small but significant proportion of rangelands are grassland communities and contain ecologically diverse and threatened ecosystems.

Grasslands are Threatened

Improper recreational use, conversion to cropland, and the societal pressures to convert grasslands into commercial or industrial developments are just a few of the many drivers causing grassland degradation (Lund 2007; Iverson 2004; Tiscornia et al. 2019). In particular, B.C.'s livestock and forage producers face challenges in preventing the overuse of pasture, adapting to the increasingly severe and frequent weather events associated with climate change, and managing harmful invasive plant species. These three challenges are discussed below.

Overgrazing

Grasslands can rapidly degrade and take years to recover following continuous and heavy grazing (Tiscornia et al. 2019). Overgrazing occurs when the forage demand exceeds the carrying capacity, or the amount of forage available for grazing animals (Teague et al. 2011; Tiscornia et al. 2019). B.C. interior grasslands historically experienced sporadic, low-intensity grazing by elk, deer, pronghorn, and bighorn sheep (Evans et al. 2012; GCC 2017). However, the introduction of large domestic cattle herds in the 1830s-50s resulted in heavy, year-round grazing (Gayton 2003) and rangeland decline. Therefore, this increase in grazing frequency and intensity placed pressure on a variety of native perennial bunchgrasses, including bluebunch wheatgrass (*Pseudoroegneria spicata*), Idaho fescue (*Festuca idahoensis*), and rough fescue (*Festuca campestris*) (Krzic et al. 2014; Meays et al. 2014; Bradfield et al. 2021).

In addition to altering plant community composition and structure (Rambo and Faeth 1999; Wan et al. 2011; Li et al. 2016), overgrazing can harm soil health. Bulk density, a measure of soil compaction, can increase in response to grazing in semi-arid rangeland when compared to adjacent ungrazed areas (Chanasyk and Naeth 1995, Krzic et al. 2014). Increased soil compaction makes root penetration difficult and, therefore, reduces water infiltration and the amount of water available to plants (Donkor et al. 2002; Byrnes et al. 2018). In grasslands, overgrazing can also expose bare ground, leading to erosion and the loss of essential soil nutrients (Iverson 2004; Metera et al. 2010; Krzic et al. 2014). Moreover, up to 40% of the carbon stored within the soil surface can be lost in overgrazed areas compared to historically ungrazed, natural grasslands (Wang et al. 2014).

Climate Change

Climate change is another concern facing B.C.'s agriculture industries. Annual increases in temperature and atmospheric $C0_2$ levels, altered precipitation patterns, and lower soil moisture values are several anticipated effects of climate change in western grasslands (Gayton 2013; Densmore-McCulloch et al. 2016; Belovsky and Slade 2020; Finch et al. 2021). These changes are expected to alter the growth, distribution, and reproductive success of grassland plants (Hamim 2005; Gayon 2013; Finch et al. 2021).

The cool season (C_3) bunchgrasses that typically dominate B.C.'s grasslands, such as bluebunch wheatgrass, are expected to withstand the increased temperatures, as they become dormant in the drier summer months (Gayton 2013). Seasonal changes may also occur where grasslands become wetter and cooler during active spring growth (May and June) and drier and hotter throughout the summer (Belovsky and Slade 2020). These changes, in addition to increased atmospheric $C0_2$ levels, may actually allow C_3 grassland species to maintain or improve their levels of productivity in response to changing climates (Taub 2010).

However, invasive plants are also known to be adaptable and highly plastic to environmental conditions (Clements and Ditommaso 2010), therefore it is expected that more frequent and severe weather events will provide opportunities for invasive plants to establish and persist (Hobbs and Huenneke 1992, Teague et al. 2008).

Invasive Species

A species is considered to be invasive if they are found outside of their natural range and cause harm to the surrounding environment, to the economy, or to society (ISCBC 2017). Once invasive plants have established, they can be difficult and costly to remove (Rankin et al. 2004). In B.C.'s Southern Interior rangelands, invasive plants have reduced forage production for livestock, and have created vulnerable, less diverse plant communities (Maxwell et al. 1992; Simberloff et al. 2013; Schuster et al. 2018).

Invasive plants can be toxic and unpalatable to livestock, and can therefore reduce forage quality. Hoary alyssum (*Berteroa incana*), for instance, is a common rangeland invader in the mustard (*Brassicaceae*) family that is toxic when ingested by horses (Madani et al. 2010). Invasive plants, such as hound's tongue (*Cynoglossum officinale*), can also have barbed seeds (burrs) that 'hitchhike' and spread rapidly by travelling on animal fur and clothing (De-Clerck Floate 1997). Furthermore, most invasive plants are prolific seed producers and can quickly overwhelm the native seed bank (Gallandt 2006), many of which can persist in the soil for years. One rangeland invasive plant in particular, spotted knapweed (*Centaurea stoebe*), threatens the livelihood of B.C.'s ranching communities and can degrade B.C.'s sensitive and endangered grassland ecosystems.

Spotted Knapweed

Spotted knapweed (*Centaurea stoebe*) is an herbaceous forb introduced from Eurasia that has invaded over 2.9 million hectares of land in North America (Martin et al. 2014). The plant is a biennial or short-lived perennial that can produce up to 1000 seeds annually (Davis et. al 1993), form dense monocultures, and can produce allelopathic chemical compounds in the soil, which in turn can inhibit native plant growth and establishment (Martin et al. 2014).

Knapweed is an economic burden, costing B.C. ranchers an estimated $13 million annually to account for cattle forage losses (Rankin et al. 2004). The widespread use of chemicals to control invasive plants is also expensive and likely to decrease in the future with increased efforts to enforce environmentally and economically sustainable weed management practices (Joyce et al. 2013). Furthermore, the development of herbicide resistance is a concern in invasive plants, especially if infestations are repeatedly treated with the same active ingredient over several years (Kumar et al. 2019; Hulme and Liu 2021). For instance, recent research found that a population of spotted knapweed in the Kootenay region of B.C. exhibited resistance to clopyralid at rates 32 times greater than the label recommendation (Magnin and Hall 2016).

Therefore, integrating multiple weed management techniques in rangelands including grazing, plant competition, biological control insects, and mowing or hand-pulling may reduce the use of herbicides and help prevent resilience in invasive plants (Lake and Minteer

2017). Thus, there is a need to develop innovative invasive plant management strategies that focus not only on weed suppression, but ecological function and rangeland productivity as a whole (Sheley et al. 1996; Wilgen et al. 2001).

Rangeland Restoration

Successful rangeland restoration projects consider the health of above and belowground site characteristics (Smreciu et al. 2003; Alemu et al. 2019). The international standards developed by the Society for Ecological Restoration define ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed." (Gann et al. 2019; Gerwing et al. 2021). Therefore, restoration activities can help degraded sites regain ecosystem function, such as improved soil nutrients or biomass production, and ecosystem structure, which includes species diversity and richness (Dobson et al. 1997; Lima et al. 2016).

Restoration activities on degraded sites typically involve human interventions, such as removing non-native plant species, revegetating a site, or modifying grazing regimes (Bradshaw 1996; Hobbs et al. 2011; Shackelford et al. 2013). Ecological succession, or natural processes (Dobson et al. 1997), can also aid in restoring degraded sites. However, primary and secondary succession, which includes soil development and the reassembly of biological communities following either natural or anthropogenic disturbances (Chang and Turner 2019), may take hundreds to thousands of years (Bradshaw 1996). Therefore, natural processes will also likely require assistance to be successful in present day restoration practices, but should be incorporated into restoration plans whenever possible (Bradshaw 1996).

Fortunately, restoration ecology is a rapidly developing field (Aronson et al. 2006; Shackelford et al. 2013; Martin 2017; Gerwig et al. 2021), and research within native grassland ecosystems is on the rise (Wang et al. 2014; Prive et al. 2021). Specific research areas of interest are the re-establishment of native plant communities' post-disturbance and the potential for soil carbon sequestration in grasslands (Conant et al. 2001; Harrower et al. 2012; Bork et al. 2020; Prive et al. 2021).

Grazing as a Restoration Tool

It is well documented that implementing improved grazing management practices can promote rangeland health and associated ecosystem services (Conant et al. 2003; Alemu et al. 2019; Bork et al. 2021). Grasslands have co-evolved with forms of natural disturbances, such as grazing from ungulates (Teague et al. 2008). Therefore, plant communities may become may become altered once the disturbance is removed. For instance, removing grazing entirely in native grasslands can deplete biodiversity; in some cases, over 60% of species have been lost in grasslands after long-term grazing suppression (Metera et al. 2010).

Moderately grazed grasslands can increase above and belowground carbon levels through compensatory growth and the turnover of plant roots (Schönbach et al. 2011). Hoof action, or treading by cattle can create small openings in the soil surface that can help native grasses establish (Savory and Parsons 1980; Metera et al. 2010). While grazers can remove and ingest large quantities of biomass on the landscape, they can also return carbon in the form of dung and nitrogen through urine (Whitehead 2020). Grazing animals can also increase the availability of forage nutrients through excrement (Teague et al. 2008), which are critical for livestock nutrition and the production of milk and muscle development (Zhai et al. 2018). Therefore, incorporating cattle grazing may be considered a beneficial tool to help restore native rangelands (Coffey 2007, GCC 2017).

Grazing management, as defined by Allen Dobb (2013), is the “manipulation of grazing to achieve an objective or a set of objectives”. Management practices are broad, and ranchers adopt grazing techniques based on their goals, landscape type, climatic conditions, and available resources (Teague et al. 2011; Heiberg and Syse 2020). Grazing management can be viewed along a “continuum” that ranges from extensive grazing (conventional, long-duration, high frequency) to management-intensive grazing (short-duration, high intensity-low frequency, adaptive multi-paddock grazing) or MiG (Dobb 2013; Denesiuk 2015; Heiberg and Syse 2020) (Figure 1.1). As a result, the labour, energy and resources required to perform MiG practices are much greater than extensive (Figure 1.1). Approximately 66% of Canadian beef producers currently use a form of extensive grazing management, whereas the remaining 34% utilize MiG (Alemu et al. 2019). However, the percentage of native grasslands being used for MiG and extensive grazing practices is unknown.

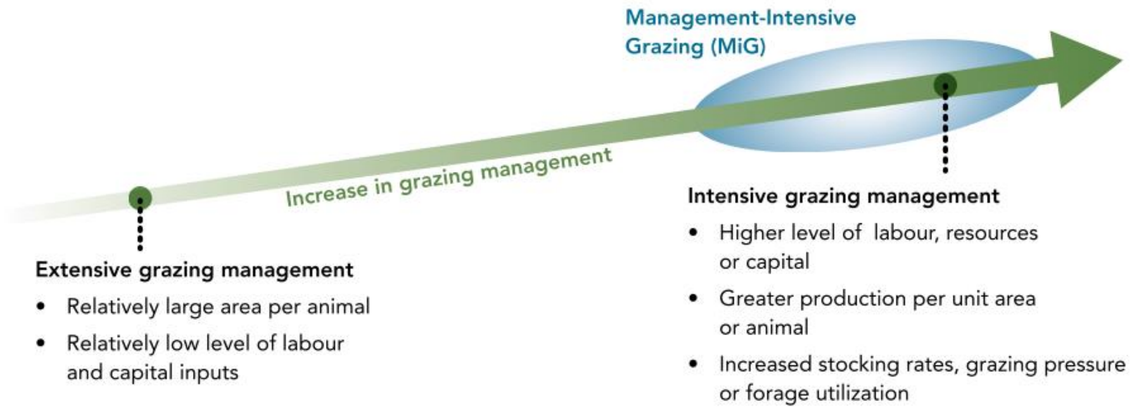


Figure 1.1. The grazing management continuum, as illustrated by Allen Dobb (2013).

Extensive Grazing

Extensive (conventional, rotational) grazing practices are characterized by large areas of land per animal for long grazing durations and require low manual labor and capital inputs (Dobb 2013) (Figure 1.2). This form of management enables cattle to influence the composition of vegetation and dominant plant species over time, as highly selected for, or palatable plants have the opportunity to be repeatedly grazed (Briske et al. 2008; Metera et al. 2010). Increased frequency and intensity of grazing can also lead to high levels of stress on forage plants, and eventually, cause mortality (Teague et al. 2008). Therefore, repeatedly grazed systems often experience a decrease in palatable forage plants and an increase in unpalatable or undesired plant species as time progresses (Baranova et al. 2019).

Ranch operations that have adopted intensive management instead of extensive have demonstrated an array of benefits in agronomic, irrigated, or seeded pasture systems (Conant et al. 2003; Teague et al. 2008; Teague et al. 2013).

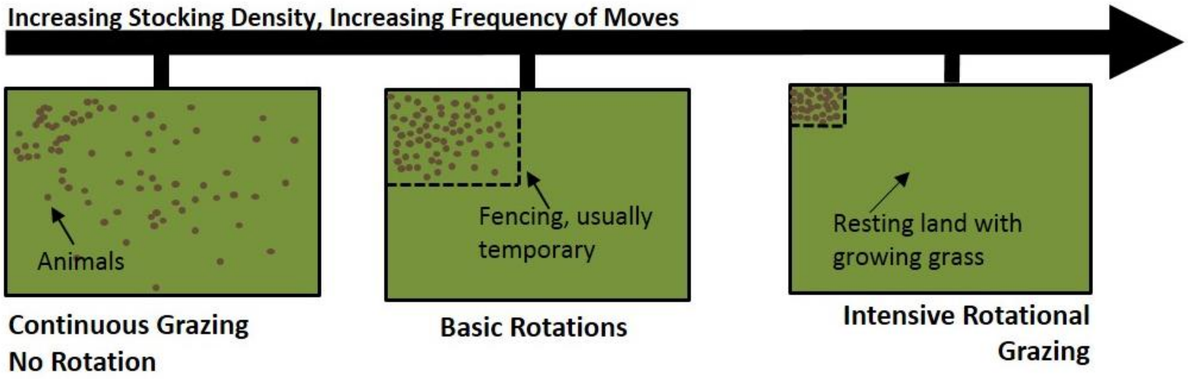


Figure 1.2. *A continuous grazing system with no rotation or fencing developments (left), basic grazing rotations (middle), and intensive rotational grazing systems (right). Photo courtesy of the Foothills Forage & Grazing Assoc.*

Management-Intensive Grazing

Management-intensive grazing (MiG), also known as adaptive paddock management (ADP) (Bork et al. 2021), involves grazing many small paddocks at high stocking densities, then moving the animals into fresh rested pasture daily, often through the use of electric fencing (Savory and Parsons 1980; Conant et al. 2003; Dobb 2013; Bork et al. 2021) (Figure 1.2). MiG practices help promote uniform forage use and provide forage species with adequate time for rest and recovery (Conant et al. 2003).

Proper grazing utilization rates are critical when practicing MiG; ideally, at least 50% or more of the plant material (by weight) should remain post-grazing (Gerrish 2005; Kyle 2015). Residual plant materials increase photosynthetic capabilities and create enhanced opportunities for regrowth (Teague et al. 2008), whereas a utilization rate greater than 50% can result in suppressed above and belowground plant growth (Briske et al. 2008). Additionally, MiG practices have been shown to reduce erosion through improved root structures (Reeder and Schuman 2002; Teague et al. 2011; Teague et al. 2013). Teague et al. (2008) claims that MiG practices have little to no negative effects on soil aggregate formation or compaction. Increases in soil organic carbon when practicing MiG have also been reported on pastureland, or land dedicated to haying or agronomic species, such as orchard grass (*Dactylis glomerata*), Kentucky bluegrass (*Poa pratensis*), and white clover (*Triflorum repens*) (Conant et al. 2003).

Ideally, we can use MiG to produce resilient rangelands, while balancing livestock production and the sustainable use of forage (Dobb 2013). However, most research on MiG has focused on irrigated or seeded pasture systems. Therefore, there is little known on the effects of MiG practices on native, semi-arid grasslands.

Targeted Grazing

Targeted or prescribed grazing is considered a form of intensive management, although the objectives shift from livestock production to vegetation management and landscape enhancement (Coffey 2007). Targeted grazing practices alter the duration, intensity, and season of grazing to achieve specific vegetation management objectives, such as invasive plant control (Bailey et al. 2019). This form of management provides commodities for the rancher, such as beef and forage production, in the process of suppressing invasive plants and creating a more productive range (Rinella and Bellows 2016). Targeted grazing, therefore, has the potential to be a restoration tool within invaded rangelands.

Knowledge Gaps & Thesis Objectives

There are several knowledge gaps that my research will attempt to address:

1) Addressing a lack of locally-relevant, applied grazing research in B.C.'s Southern interior, semi-arid rangelands.
2) Most applications of intensive grazing management are performed on irrigated, or agronomic (seeded) pastures; will we be able to detect short-term effects of intensive grazing in semi-arid, native rangeland?
3) Will targeted cattle grazing help suppress the invasive plant spotted knapweed?

The overarching purpose of this study was to assess whether intensive grazing management practices could aid in restoring invaded, semi-arid rangelands in the Southern Interior of B.C.

To do this, we conducted a 3-year controlled field experiment which tested the use of MiG, targeted, and extensive cattle grazing for their effects on plant community structure, diversity, productivity and soil properties. This field study is summarized in Chapter 2, ‘**Testing Intensive Cattle Grazing Management to Restore Invaded, Semi-Arid Rangelands**’.

A secondary research objective was to test targeted cattle grazing to help control the growth and spread of spotted knapweed. In the field, we compared the growth and seed production of spotted knapweed plants that had been targeted by cattle or left ungrazed (control). Soil seed bank samples were collected post-grazing and grown in the greenhouse to compare knapweed seedling recruitment. Soil seed bank composition, size, and density were also described for restoration purposes. This field and greenhouse study is summarized in Chapter 3, **‘Testing Targeted Cattle Grazing to Supress Spotted Knapweed (*Centaurea stoebe*) in Semi-Arid Rangelands’**

Chapter 4, ‘**Research Summary and Conclusions**’ considers the management implications of my findings and provides recommendations for future research, particularly for implementing targeted grazing on a landscape scale.

REFERENCES

Alemu A, Kröbel R, McConkey B, Iwaasa A. 2019. Effect of increasing species diversity and grazing management on pasture productivity, animal performance, and soil carbon sequestration of re-established pasture in Canadian prairie. Animals. 9(4):127.

Archer SR, Andersen EM, Predick KI, Schwinning S, Steidl RJ, Woods SR. 2017. Woody plant encroachment: causes and consequences. In: Briske DD, editor. Rangeland systems: processes, management and challenges. Cham, Switzerland: Springer Nature. p. 25–84.

Aronson J, Clewell AF, Blignaut JN, Milton SJ. 2006. Ecological restoration: A new frontier for nature conservation and economics. J Nat Conserv. 14(3–4):135–139.

Bailey DW, Mosley JC, Estell RE, Cibils AF, Horney M, Hendrickson JR, Walker JW, Launchbaugh KL, Burritt EA. 2019. Synthesis Paper: Targeted livestock grazing: prescription for healthy rangelands. Rangel Ecol Manag. 72(6):865–877.

Baranova A, Oldeland J, Wang S li, Schickhoff U. 2019. Grazing impact on forage quality and macronutrient content of rangelands in Qilian Mountains, NW China. J Mt Sci. 16(1):43–53.

Beck PA, Beck MR, Gunter SA, Biermacher JT, Gillen RL. 2020. Stocking rate impacts performance and economics of grazing beef steers on mixed-grass prairies of the Southern Great Plains. Transl Anim Sci. 4(3):1–13.

Belovsky GE, Slade JB. 2020. Climate change and primary production: Forty years in a bunchgrass prairie. PLoS One. 15(12 December):1–21.

Bradshaw AD. 1996. Underlying principles of restoration. Can J Fish Aquat Sci. 53(SUPPL. 1):3–9. doi:10.1139/cjfas-53-s1-3.

British Columbia Cattleman’s Association (BCCA). [Internet]. 2020. BC Beef Cattle Industry. Kamloops, BC: British Columbia Cattlemen’s Association. Available from: https://www.cattlemen.bc.ca/industry.htm

[BCMoF] British Columbia Ministry of Forests. 2000. Range use plan guidebook. 2nd ed. Victoria, BC: Government of British Columbia.

Blackstock M, McAllister R. 2004. First nations perspectives on the grasslands of the Interior of British Columbia. J Ecol Anthropol. 8(1):24–46.

Bork EW, Raatz LL, Carlyle CN, Hewins DB, Thompson KA. 2020. Soil carbon increases with long-term cattle stocking in northern temperate grasslands. Soil Use Manag. 36(3):387–399.

Chanasyk DS, Naeth MA. 1995. Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. Can J Soil Sci. 75(4):551–557.

Clayton JS, Ehrlich WA, Cann DB, Day JH, Marshall IB. 1977. Soils of Canada. Canada Department of Agriculture, Research Branch: Ottawa, ON. Volume 1, p. 243.

Clements DR, Ditommaso A. 2011. Climate change and weed adaptation: Can evolution of invasive plants lead to greater range expansion than forecasted? Weed Res. 51(3):227–240.

Coffey L. 2007. Targeted Grazing: A natural approach to vegetation management and landscape enhancement. Launchbaugh KL, editor. Centennial, CO: American Sheep Industry Association.

Conant RT, Paustian K, Elliott ET. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl. 11(2):343–355.

Conant RT, Six J, Paustian K. 2003. Land use effects on soil carbon fractions in the southeastern United States. Biol Fertil Soils. 38(6):386–392.

Davis ES, Fay PK, Chicoine TK, Lacey CA. 1993. Persistence of spotted knapweed (*Centaurea maculosa*) seed in soil. Weed Sci. 41(1):57–61.

De Bruijn SL, Bork EW, Grekul CW. 2010. Neighbor defoliation regulates Canada thistle (*Cirsium arvense*) in pasture by mediating interspecific competition. Crop Prot. 29(12):1489–1495.

Denesiuk DR. 2017. Grazing management as a climate change adaptation and mitigation strategy. Thompson Rivers University.

Densmore-McCulloch JA, Thompson DL, Fraser LH. 2016. Short-term effects of changing precipitation patterns on shrub-steppe grasslands: Seasonal watering is more important than frequency of watering events. PLoS One. 11(12).

Dobb, A. 2013. BC farm practices and climate change adaptation: Management-intensive grazing. BC Agriculture and Food Climate Action Initiative. 22p.

Dobson AP, Bradshaw AD, Baker AJM. 1997. Hopes for the future: restoration ecology and conservation biology. Science (80-). 277(5325):515–522.

Donkor NT, Gedir J V., Hudson RJ, Bork EW, Chanasyk DS, Naeth MA. 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. Can J Soil Sci. 82(1):1–8.

Evans CRW, Krzic M, Broersma K, Thompson DJ. 2012. Long-term grazing effects on grassland soil properties in southern British Columbia. Can J Soil Sci. 92(4):685–693.

Fraser LH, Carlyle CN. 2011. Is spotted knapweed (*Centaurea stoebe* L.) patch size related to the effect on soil and vegetation properties? Plant Ecol. 212(6):975–983.

Gallandt ER. 2006. How can we target the weed seedbank? Weed Sci. 54(3):588–596.

Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J (2019) International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology 27:S1–S46

Gayton DV. 2003. British Columbia grasslands: Monitoring vegetation change. Kamloops, BC: FORREX–Forest Research Extension Partnership. FORREX Series 7. 49p.

Gerwing TG, Hawkes VC, Gann GD, Murphy SD. 2021. Restoration, reclamation, and rehabilitation: on the need for, and positing a definition of, ecological reclamation. Restor Ecol.:2–5.

Grasslands Conservation Council of British Columbia (GCC). (2017). Managing BC grasslands: an overview. Kamloops, BC. 22p.

Harrower W, Carlyle C, DeKoning P, and Fraser L. 2012. Managing rangelands for carbon: Assessing the viability of carbon offset markets for British Columbia ranchers. 78p.

Heiberg EJ, Syse KL. 2020. Farming autonomy: Canadian beef farmers reclaiming the grass through management-intensive grazing practices. Org Agric. 10(4):471–486.

Hobbs RJ, Huenneke LF. 1992. Disturbance, diversity, and invasion: Implications for conservation. Conserv Biol. 6(3):324–337.

Hulme PE, Liu W. 2021. Species prevalence and plant traits discriminate between herbicide resistant and susceptible weeds. Pest Manag Sci. (August).

Invasive Species Council of British Columbia (ISCBC). 2017. Invasive species strategy for British Columbia 2017-2022. Williams Lake, BC: Invasive Species Council of BC. 11p.

Iverson K. 2004. Grasslands of the southern interior. Victoria, BC: Ministry of Sustainable Resource Management. 6p.

Joyce LA, Briske DD, Brown JR, Polley HW, McCarl BA, Bailey DW. 2013. Climate change and North American rangelands: assessment of mitigation and adaptation strategies. Rangel Ecol Manag. 66(5):512–528.

Knochel DG, Monson ND, Seastedt TR. 2010. Additive effects of aboveground and belowground herbivores on the dominance of spotted knapweed (*Centaurea stoebe*). Oecologia. 164(3):701–712.

Krzic M, Lamagna SF, Newman RF, Bradfield G, Wallace BM. 2014. Long-term grazing effects on rough fescue grassland soils in southern British Columbia. Can J Soil Sci. 94(3):337–345.

Kyle, J. [Internet]. 2015. Take half and leave half: pasture management strategies for sustainable productivity. Guelph, Ontario: Ontario Ministry of Agriculture, Food and Rural Affairs; [updated July 6 2015]. Available from: http://www.omafra.gov.on.ca/english/livestock/beef/news/vbn0715a1.htm

Kumar A., Choudhary T., Das S., Meena S.K. 2019. Weed seed bank: impacts and management for future crop production. In: Hasanuzzaman M. (eds) Agronomic Crops. Springer, Singapore.

Lake EC, Minteer CR. 2018. A review of the integration of classical biological control with other techniques to manage invasive weeds in natural areas and rangelands. BioControl. 63(1):71–86. doi:10.1007/s10526-017-9853-5.

Launchbaugh KL, Walker JW, Daines R. 2006. Targeted grazing: a new approach to vegetation management and landscape enhancement. Centennial, CO: American Sheep Industry Association 199 pp.

Li W, Xu F, Zheng S, Taube F, Bai Y. 2017. Patterns and thresholds of grazing-induced changes in community structure and ecosystem functioning: species-level responses and the critical role of species traits. J Appl Ecol. 54(3):963–975.

Li J, Ramirez GH, Kiani M, Quideau S, Smith E, Janzen H, Larney F, Puurveen D. 2018. Soil organic matter dynamics in long-term temperate agroecosystems: Rotation and nutrient addition effects. Can J Soil Sci. 98(2):232–245.

Lima AT, Mitchell K, O'Connell DW, Verhoeven J, Van Cappellen P. 2016. The legacy of surface mining: Remediation, restoration, reclamation and rehabilitation. Environ Sci Policy. 66:227–233.

Lloyd D, Iverson K, Mackenzie K, Richardson H, Jeffries L. 2019. Laurie Guichon Memorial Grasslands Interpretive Site: A Baseline Inventory. Kamloops, BC. Grassland Conservation Council of British Columbia. 98 p.

Lund GH. 2007. Accounting for the world's rangelands. Rangelands. 29(1):3–10.

Madani H, Stopps G, Upadhyaya MK. 2010. Seed germination ecophysiology of hoary alyssum (*Berteroa incana* L.) in different temperature, dry heat and anaerobiosis conditions. J Plant Ecophysiol. 2(2010):121–126.

Mangin AR, Hall LM. 2016. First report: spotted knapweed (*Centaurea stoebe*) resistance to auxinic herbicides. Can J Plant Sci. 96(6):928–931.

Martin DM. 2017. Ecological restoration should be redefined for the twenty-first century. Restor Ecol. 25(5):668–673.

Martin LM, MacDonald NW, Brown TE. 2014. Native plant establishment success influenced by spotted knapweed (*Centaurea stoebe*) control method. Ecol Restor. 32(3):282–294.

Maxwell JF, Drinkwater R, Clark D, Hall JW. 1992. Effect of grazing, spraying, and seeding on knapweed in British Columbia. J Range Manag. 45(2):180.

Meays CL, Laliberte AS, Doescher PS. 2000. Defoliation response of bluebunch wheatgrass and crested wheatgrass: why we cannot graze these two species in the same manner. Rangelands. 22(6):6–8.

Metera E, Sakowski T, Słoniewski K, Romanowicz B. 2010. Grazing as a tool to maintain biodiversity of grassland - a review. Anim Sci Pap Reports. 28(4):315–334.

Palit R, Gramig G, Dekeyser ES. 2021. Kentucky bluegrass invasion in the northern great plains and prospective management approaches to mitigate its spread. Plants. 10(4):1–14.

Prive K, Orr MR, Kilkenny FF, Reauter RJ, Prendeville HR. 2021. Phenological variation in bluebunch wheatgrass (*Pseudoroeneria spicata*): implications for seed sourcing, harvest, and restoration. Land. 10(1064):1–10.

Rambo JL, Faeth SH. 1999. Effect of vertebrate grazing on plant and insect community structure. Conserv Biol. 13(5):1047–1054.

Rapp, R. 2018. Pasture principles from the soil up. Farm Talk Newspaper. Sept 26, 2018.

Rankin C, Booth J, Cannings S. 2004. Invasive alien species framework for BC: identifying and addressing threats to biodiversity. 96p.

Reeder JD and Schuman GE. 2002. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environmental Pollution 116:457- 463.

Rinella MJ, Bellows SE. 2016. Evidence-targeted grazing benefits to invaded rangelands can increase over extended time frames. Rangel Ecol Manag. 69(3):169–172.

Savory A, Parsons SD. 1980. The Savory Grazing Method. Rangelands. 2(6):234–237.

Schaub S, Buchmann N, Lüscher A, Finger R. 2020. Economic benefits from plant species diversity in intensively managed grasslands. Ecol Econ. 168:1-12.

Schuster MJ, Wragg PD, Reich PB. 2018. Using revegetation to suppress invasive plants in grasslands and forests. J Appl Ecol. 55(5):2362–2373.

Shackelford N, Hobbs RJ, Burgar JM, Erickson TE, Fontaine JB, Laliberté E, Ramalho CE, Perring MP, Standish RJ. 2013. Primed for change: Developing ecological restoration for the 21st century. Restor Ecol. 21(3):297–304.

Sheley RL, Svejcar T, Maxwell B. 1996. A theoretical framework for developing successional weed management strategies on rangeland. Weed Technol. 10(4):766–773.

Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, et al. 2013. Impacts of biological invasions: What's what and the way forward. Trends Ecol Evol. 28(1):58–66.

Smreciu A, Sinton H, Walker D, Bietz J. 2003. Establishing native plant communities. Orey D, editor. Edmonton, Alberta: Alberta Agriculture, Food and Rural Development. 93p.

Teague R, Provenza F, Kreuter U, Steffens T, Barnes M. 2013. Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? J Environ Manage. 128:699–717.

Teague WR, Dowhower SL, Baker SA, Haile N, DeLaune PB, Conover DM. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric Ecosyst Environ. 141(3–4):310–322.

Teague R, Provenza F, Norton B, Steffens T, Barnes M, Kothmann M, Roath R. 2008. Benefits of multi-paddock grazing management on rangelands: Limitations of experimental grazing research and knowledge gaps. Grasslands Ecol Manag Restor.:41–80.

Tiscornia G, Jaurena M, Baethgen W. 2019. Drivers, process, and consequences of native grassland degradation: Insights from a literature review and a survey in Río de la Plata grasslands. Agronomy. 9(5):8–12.

Toledo D, Sanderson M, Spaeth K, Hendrickson J, Printz J. 2014. Extent of Kentucky bluegrass and its effect on native plant species diversity and ecosystem services in the northern great plains of the United States. Invasive Plant Sci Manag. 7(4):543–552.

Wan H, Bai Y, Schönbach P, Gierus M, Taube F. 2011. Effects of grazing management system on plant community structure and functioning in a semiarid steppe: Scaling from species to community. Plant Soil. 340(1):215–226.

Wang X, Vandenbygaart AJ, McConkey BC. 2014. Land management history of Canadian grasslands and the impact on soil carbon storage. Rangel Ecol Manag. 67(4):333–343.

Whitehead D. 2020. Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands. Front Sustain Food Syst. 4(October):1–7.

Wikeem BM, Mclean A, Quinton D, Bawtree A. 1993. An overview of the forage resource and beef production on Crown land in British Columbia. Can J Anim Sci. 73(4):779–794. doi:10.4141/cjas93-081.

Wilgen B van, Richardson D, Higgins S. 2001. Integrated control of invasive alien plants in terrestrial ecosystems. L Use Water Resour Res. 5:6.

Zhai X, Zhang Y, Wang K, Chen Q, Li S, Huang D. 2018. Grazing effects on the nutritive value of dominant species in steppe grasslands of northern China. BMC Ecol. 18(1):1–9.

2. CHAPTER 2

TESTING INTENSIVE CATTLE GRAZING MANAGEMENT TO RESTORE INVADED, SEMI-ARID RANGELANDS

General Introduction

Grasslands provide essential ecosystem goods and services, such as forage production for livestock, wildlife habitat, soil carbon sequestration, biodiversity, and more (Wikeem and Wikeem 2004; Dobb 2013; Augustine et al. 2020; Bork et al. 2021). However, grasslands are sensitive and can rapidly degrade in response to disturbance. It may take years to decades for a disturbed grassland to return to its previous vegetation community and state of ecological functioning (Iverson 2004; Tiscornia et al. 2019).

The introduction of non-native, harmful invasive plant species threatens rangeland ecosystem goods and services (Wikeem and Wikeem 2004; Clements et al. 2007). Spotted knapweed (*Centaurea stoebe*), for instance, is an aggressive, drought-tolerant invader that can disrupt soil stability and outcompete native plant species (Fraser and Carlyle 2011; Gayton and Miller 2012). Periodic drought can also make rangeland restoration efforts, such as seeding and revegetation, difficult due to insufficient moisture and competition from drought-adapted species (Wikeem and Wikeem 2004; Evans et al. 2012; Krzic et al. 2014). Therefore, the ranching and scientific communities alike have been developing improved grazing management strategies in an effort to help restore native rangelands following mild to severe disturbance events (Conant and Paustian 2001; Dobb 2013; Chen et al. 2015; Döbert et al. 2021). Several of these grazing management systems are described below.

Management-intensive Grazing

Management-intensive grazing (MiG), otherwise known as adaptive multi-paddock management (AMP), involves grazing at moderate to high stocking rates, then frequently moving the livestock into fresh rested pasture (Savory and Parsons 1980; Dobb 2013; Mann and Sherren 2018; Bork et al. 2021). In theory, longer periods of rest between defoliation events - especially during active spring growth – along with a generous stubble height, allow grazed plants to better regrow and recover (Dobb 2013; Augestine et al. 2020; Bork et al. 2021; Döbert et al. 2021). When practicing MiG, livestock also return carbon and nitrogen-rich manure and urine back into the system at a more uniform distribution (Gupta et al. 2016; Marie et al. 2018). Cow manure, in particular, contains high concentrations of nitrogen, phosphorus, and sulfur, all of which are essential nutrients for plant growth (Raiesi et al. 2006; Almeida et al. 2019; Bader et al. 2021). Increases in plant productivity, or above and belowground biomass, also encourages soil organic matter (SOM) formation and increases the potential for soil carbon storage (Lal 2009; Li et al. 2018; Whitehead 2020).

MiG is commonly practiced on agronomic pastureland, or land that consists of maintained forage crops (Conant et al. 2003; Dobb 2013). These areas are often more accessible for machinery, and fencing and irrigation developments may already exist or could be installed more readily than on native rangeland. However, the feasibility of implementing MiG on semi-arid rangeland hasn't been investigated thoroughly, nor have the ecosystem benefits been explored.

Extensive Grazing

Extensive (conventional, rotational) grazing is widely used in the management of native rangeland pastures, largely because irrigation and fencing or manual labour may be limited (DiTomaso 2000; Dobb 2013; Heiberg and Syse 2020). Extensive grazing still involves rotating livestock into rested pastures; however, unlike MiG, the pastures are larger in size and grazed for longer time periods, resulting in a lower number of animals per unit land area and less manual labour and capital inputs for the ranching operation (Dobb 2013; Heiberg and Syse 2020).

Forage selectivity plays a role in extensive grazing management. When provided with a choice, livestock will select for preferred forages such as perennial bunchgrasses (Metera et al. 2010; Pauler et al. 2020). Therefore, selectivity and overgrazing can be a concern if there is an opportunity for livestock to re-graze preferred plants, or if there is limited time for the plants to recover following the grazing event. Overgrazing limits plant productivity and suppresses root formation, leading to issues with soil stability, erosion and compaction (Metera et al. 2010; Krzic et al. 2014). That being said, if plants are provided with sufficient rest between grazing events or rotations, livestock selectivity can encourage the formation of a ‘mosaic’ landscape, where plant communities display a more heterogenous and diverse structure (Pavlů et al. 2006; Metera et al. 2010).

Targeted Grazing

Targeted grazing is another intensive land management tool which utilizes grazing animals to achieve ecological, economic, or other operational goals such as weed suppression and control, maintenance or enhancement of wildlife habitat, and improved biodiversity (Coffey 2007; Bailey et al. 2019; Rhodes et al. 2021). Targeted grazing has increased in popularity in recent years because it is cost-effective, can be used in a variety of environments, and can provide long-lasting results and commodities for the rancher (Diamond et al. 2009; Davy and Rinella 2017). Areas that are difficult to access (i.e., steep terrain) or are in close proximity to water can be reached through targeted grazing, and it often provides the opportunity to reduce or halt the use of herbicides to help control undesired plant species (Davy and Rinella 2017; Bailey et al. 2019). Cattle, for instance, have been used to help reduce fire fuel loads and help create fire breaks by grazing the highly flammable introduced grass, cheatgrass (*Bromus tectorum*) when it is palatable in the spring (Diamond et al. 2009).

Environmental Responses to Grazing Management

Vegetation Responses

Overall, it is well understood that grazing management can alter the structure and function of plant communities (Hobbs and Huenneke 1992; Li et al. 2017). Native perennial bunchgrasses such as rough fescue (*Festuca scabrella*) and bluebunch wheatgrass (*Pseudoroegneria spicata*) are sensitive to heavy and repeated grazing, especially during active spring growth (Meays et al. 2014). Subsequently, these species experience restricted above and belowground growth and produce fewer viable seeds (Krzic et al. 2014; Meays et al. 2014; GCC 2017). Furthermore, introduced, drought-tolerant perennials such as Kentucky bluegrass (*Poa pratensis*) and crested wheatgrass (*Agropyron cristatum*) can withstand heavy grazing pressure (Meays et al. 2014; Palit et al. 2021). Therefore, both species of introduced grass can dominate the slow-growing native species and transform diverse plant communities into uniform stands when heavily grazed (Palit et al. 2021).

Soil Responses

Soils are also an integral component within grassland ecosystems and can be influenced by changes in grazing management. Season-long or continuous grazing can increase bulk density and disrupt soil aggregates (Donkor et al. 2002), making it more difficult for plant roots to penetrate the soil and access essential water and nutrients (Lee et al. 2014; Tiscornia et al. 2019; Shrestha et al. 2020). Furthermore, when managed accordingly, grasslands can act as a carbon sink and, in turn, promote rangeland restoration (Scurlock and Hall 1998; Tiscornia et al. 2019; Shrestha et al. 2020). In grasslands, approximately 10% of organic carbon is held within aboveground biomass, whereas the remaining 90% is stored within the soil organic matter (SOM) (Reeder and Schuman 2002). SOM is often created through the deposition of plant litter and plays a significant role in improving soil chemical and physical properties, such as nutrient storage and retention, water holding capacity, and aggregation (Conant et al. 2001; Smith et al. 2015; Lavallee et al. 2020). The removal of plant litter and SOM can also suppress microbial activity (Mohammadi et al. 2011; Witzgall et al. 2021) and slow the decomposition of organic matter, which subsequently alters the nutrients available for plants and opportunity for soil carbon storage (Raiesi et al. 2006; Whitehead 2020).

Particulate and Mineral-Associated Organic Matter and Soil Fractionation

To better understand the potential for long-term soil carbon storage and changes in SOM formation within semi-arid rangelands, isolating the particulate organic matter (POM) from the mineral-associated organic matter (MAOM) within bulk soil is recommended (Li et al. 2018; Popleau et al. 2018; Lavallee et al. 2020). Particulate organic matter is generally created through the deposition of plant litter and root fragments, and may be modified by soil biota (Smith et al. 2015; Lavallee et al. 2020), whereas MAOM is made up of singular, microscopic organic molecules that are tightly bound to silt and clay-sized particles (< 63 µm) (Lavallee et al. 2020). The main difference between POM and MAOM is that POM often has no protective mechanism or is located with larger soil aggregates (> 63 µm), which makes POM more susceptible to decomposition and more vulnerable to changes in land management (Lavallee et al. 2020). Additionally, the carbon-nitrogen (C-N ratio) is generally lower in MAOM, and it contains nutrients and carbon compounds that are readily available for use by soil microorganisms and plants (Lavallee et al. 2020; Witzgall et al. 2021). Moreover, MAOM is depicted as the ‘long-term’ soil carbon storage and is estimated to have a residence time of decades to centuries, whereas POM can persist within the soil for decades to less than a decade (Poeplau et al. 2018; Lavallee et al. 2020.

Fractionation is a procedure that separates soils into multiple particle sizes, that helps to understand and recognize how carbon forms, persists, and functions within the soil itself (de Moraes et al. 2017; Hewins et al. 2018; Popleau et al. 2018; Lavallee et al. 2020). An assessment of particulate and mineral-associated organic matter may provide insight into how carbon is stored in response to rapid changes in land management, more specifically the alteration of grazing practices in semi-arid rangelands (Conant et al. 2003; de Moraes et al. 2017). Furthermore, investigating the influence of grazing management on soil carbon sequestration may aid in developing climate change mitigation strategies.

Research Objectives

A three-year controlled field experiment tested the use of MiG, extensive, and targeted cattle grazing for their effects on plant community structure, diversity, productivity and soil properties in B.C.’s southern interior rangelands.

The hypothesis was that intensive grazing management practices would improve the condition of B.C.’s southern interior rangelands, such that intensively-grazed pastures would demonstrate increased native plant cover, productivity, and improved diversity indices compared to extensive grazing. Whereas extensive grazing would exhibit more bare ground, less plant litter, and greater cover and productivity of introduced species than the intensively-grazed pastures. Additionally, spotted knapweed cover and productivity would decrease in response to the targeted grazing treatment. Finally, the extensively grazed pasture would exhibit greater bulk density and less soil organic matter, carbon, and nitrogen when compared to intensively grazed pastures.

Forage nutritive values are also reported in this chapter to describe the forage quality of the spotted knapweed at the point of the targeted grazing treatment (late-July) versus the mixed grass community in late-July and mid-September.

Materials and Methods

Research plots were located in Drum Lake pasture, east of Merritt, and approximately 3 km north of the Laurie Guichon Memorial Grasslands Interpretative Site (50° 5'41.89"N, 120°40'25.72"W; elevation: 1052-1065m) (Figure 2.1). Drum Lake pasture is located within the grassland phase of the Thompson very dry, hot Interior Douglas-fir (IDFxh2a) biogeoclimatic zone (Newman et al. 2011). The mean annual precipitation is 350-400mm, 35% of it falling as snow (Lloyd et al. 2019). Precipitation data for the 2019 and 2020 growing seasons (May 1st – Sept 30th) were retrieved from an Environment and Climate Change Canada weather station (Table 2.1). The vegetation community of the IDFxh2a zone is dominated by bluebunch wheatgrass (*Pseudoroegneria spicata*), rough fescue (*Festuca campestris*), Kentucky bluegrass (*Poa pratensis*), and silky lupine (*Lupinus sericeus*) (Lloyd et al. 1990).

Figure 2.1. *Looking south-east towards Drum Lake in late June.*

Chutter Ranch Ltd. operates under a range tenure where their approximately 500 cow/calf pairs graze Drum Lake following a spring/fall grazing rotation. In odd years cattle graze for 10 days in early June and in even years cattle graze for 10 days in mid-September (Table 2.2). The Chutter Ranch Ltd. 2017-2021 Range Use Plan (RUP) set the target browse utilization rate at 25% of the annual plant growth.

Table 2.1. *Summarized rainfall (mm) values for each month of the growing season (May to September) in 2019 and 2020. Data retrieved from weather station identifier # 1125073, located in Merritt, British Columbia (ECCC 2021).*

	Total Rainfall (mm)	
Month	**2019**	**2020**
May	42.5	59.0
June	50.0	47.6
July	29.4	18.4
August	12.8	5.0
September	59.0	7.0
Total	**193.7**	**137**

Table 2.2. *Description of the grazing schedule for Drum Lake pasture as outlined in the 2017 - 2021 RUP prepared by Chutter Ranch Ltd.*

	Even years	**Odd years**
Pasture name	Drum Lake	Drum Lake
Period of use	Sept 19 - 28	June 1 - 10
No. and class of livestock	500 C/C*	500 C/C* 20 Bulls

*C/C = cow-calf pairs

Experimental Design (Field Grazing Trials)

In May 2018, three 50 m by 50 m electric fence treatment enclosures were established (Figure 2.2). Stocking rate was 0.8 animal unit months (AUM) ha^{-1} for the grazing treatments, where cattle numbers and timing were controlled such that MiG was ten cow/calf (C/C) pairs for one day at the end of the summer growing season (mid-September), extensive was one C/C pair for ten days at the end of the summer growing season, and targeted was ten C/C pairs for one day at the height of spotted knapweed flowering (late July-early August). Baseline (pre-treatment) plant cover data was combined among all treatment enclosures; the baseline cover data is referred to as the 'control' in this experiment. No baseline data was collected for the soil or biomass data, therefore, biomass and soil data collected in 2019 and 2020 were combined by grazing treatment.

Grazing trials commenced in July 2018 and continued annually for three years (2018-2020).

Ethics Statement

This research was carried out under Thompson Rivers University Animal Care and Use Protocol No. 101899.

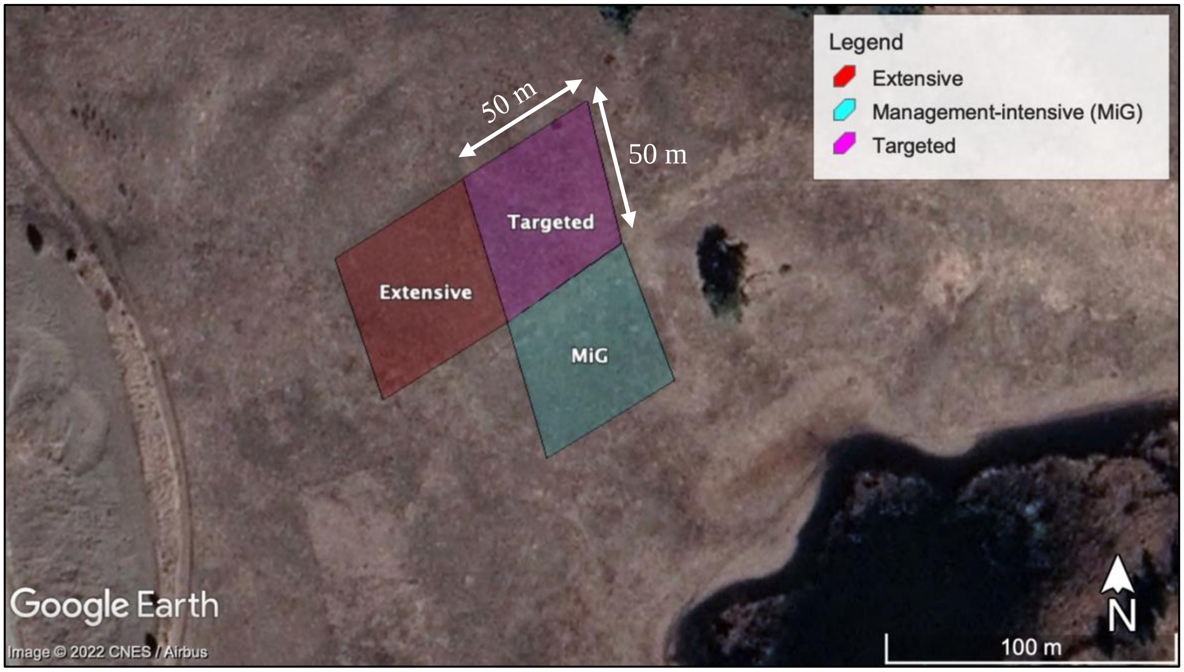


Figure 2.2. *Map depicting the grazing treatment enclosures, at Drum Lake pasture in Merritt, BC.*

Vegetation Sampling

Plant Community Composition & Diversity

Vegetation surveys were conducted annually in late June where species composition was estimated within each treatment enclosure. Ten 0.25 m^2 quadrats were placed by generating random numbers within a 50 m x 50 m sampling grid (Random.org). Percent canopy cover was used to measure plant species and ground parameters including bare ground, litter, rock, cryptogamic crust and dung. Percent cover values were allowed to exceed 100%. A two-meter buffer zone existed between all sampling quadrats and the electric fencing to reduce edge effects.

Plant species were assigned into the following categories using the electronic database, E-Flora B.C. (Klinkenberg 2021): native grasses, introduced grasses, native forbs, and invasive forbs in an effort to better understand plant community responses to the grazing treatments. Shannon (H') and Simpson (D) diversity indices were calculated with species cover data for each treatment.

Biomass

Biomass clippings were collected prior to grazing treatments in late-July and mid-September of 2019 and 2020 to determine available forage and forage quality at the point of grazing. Biomass was harvested within ten randomly placed 0.25 m^2 quadrat frames to ground height, then sorted into the following categories: mixed grasses, mixed forbs, spotted knapweed, and litter (standing and ground). Immediately (24-48 hours) following grazing, biomass clipping was repeated to estimate the biomass utilized by cattle. Biomass utilization was estimated by calculating the difference between the pre and post grazing total biomass (excluding litter). Samples were oven-dried at 65°C for 48 hours, then weighed on an analytical balance in preparation for forage nutritive analysis.

Forage Nutritive Values

Wet chemistry analyses were conducted by Fraser Valley Analytical services LTD in Abbotsford, B.C. The nutritive values of the mixed grass community at two time periods, which coincided with the intensive grazing trials (late July and early September), and spotted knapweed at the point of targeted grazing (late-July) were measured. Six biomass subsamples were selected from each category based on the largest sample quantities (by weight) and were packaged in plastic Ziploc bags. The following parameters were measured: acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), crude protein (CP), calcium, phosphorus, magnesium, potassium, sodium, iron, manganese, zinc and copper.

Soil Sampling

Soil samples were collected in July 2019 and in October 2020 within each treatment enclosure along two sampling transects and within nine 1 m by 1 m quadrat frames (Figure 2.3). Within each 1 m^2 quadrat, four holes were dug to a depth of 20 cm. Soil samples were collected at two depth intervals (0-10 cm and 10-20 cm) by excavating the sidewalls of the holes and pooling the samples by depth for a total of 36 soil cores per enclosure and 108 soil cores annually.

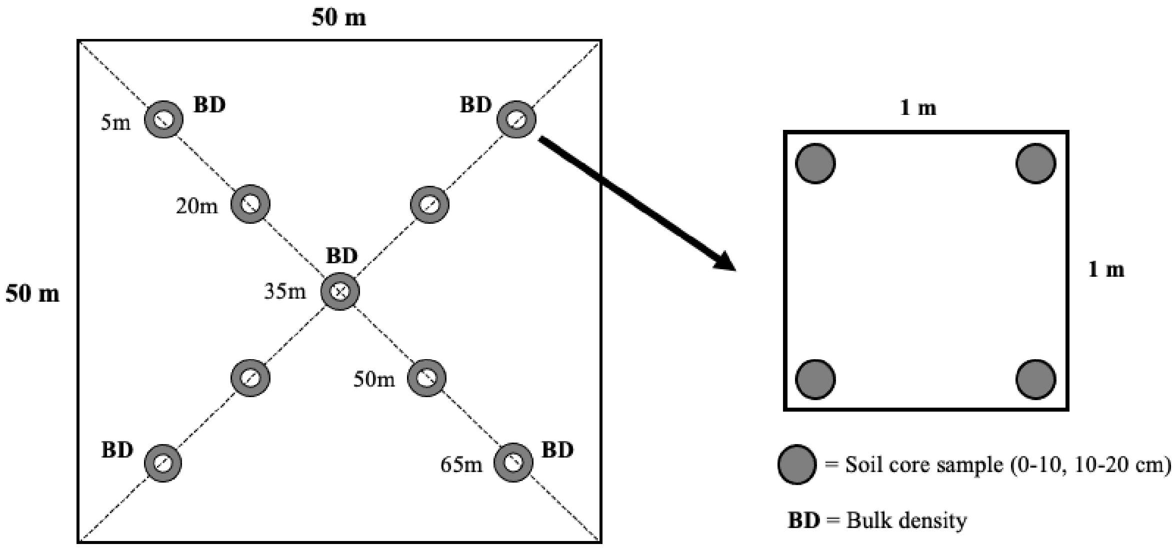


Figure 2.3. *Soil sampling grid within each treatment enclosure depicting main soil sampling points and the bulk density sampling points.*

Bulk Density

In October 2020, five bulk density samples were collected within each enclosure using the excavation method (Figure 2.3), as described by Krzic et al. 2010. The excavation method is recommended for gravelly soil and involves digging a hole approximately 1000 cm^3 in size, lining the hole with thin plastic, then filling the hole with a measured volume of water (Krzic et al. 2010). Bulk density samples were dried at 105°C for 24 hours and weighed. Coarse fragments (> 2mm in diameter) were removed and bulk density was calculated as “the mass of dry, coarse fragment-free soil per unit volume of the excavated soil” (Krzic et al. 2010).

Soil pH

Soil samples were oven dried at 30°C until a constant weight was reached, then sifted through a 2 mm mesh sieve and stored in paper bags. Soil pH was measured though a 1:2.5 ratio of 2 mm sieved, dried soil and distilled water (10 grams of dried soil with 25 mL of distilled water). The sample was shaken for 1 minute, centrifuged at 4000 rpm for 3-4 minutes, left to stand for at least 30 minutes, then the pH of the suspended water was read with a three-point calibrated pH meter (Nag 2014).

Soil Organic Matter (SOM)

Loss on ignition (LOI) techniques were used to measure soil organic matter (SOM) content (Wang et al. 2011). For each dried and 2 mm-sieved soil sample, approximately 1.5 g of soil was placed into a 105°C oven for 12-16 hours to remove excess moisture, then weighed. Soils dried at 105°C were placed into a muffle oven at 500°C for five hours, then transferred into a desiccator for one hour before re-weighing. SOM was then calculated as the soil weight loss between at 500°C and 105°C (Wang et al. 2011; Richardson 2015).

Soil Particulate Fractionation

Within each treatment enclosure five of the nine soil sampling points (at two sampling depths) were randomly selected for a modified soil particulate fractionation procedure described as ‘Par + Den 5’ by Poeplau et al. (2018) (Figure 2.4). This procedure minimizes the disruption of POM through ‘gentle’ agitation using glass beads instead of a centrifuge. The modifications for the Par + Den 5 method are described in the protocol from the Summerland Research and Development Centre (SuRDC), a research centre associated with Agriculture and Agri-food Canada (Appendix 2).

Each sample of 50 g dried, 2 mm-sieved soil was shaken overnight (16 hr) at 225 rpm on an orbital shaker with glass beads to disperse aggregates. The suspended soils were passed through a 63 µm sieve, then separated into 1) fine and coarse sands (> 63 µm), 2) silt and clay particles (< 63 µm), and particulate organic matter or POM (> 63 µm). The majority of POM in the soil was located in the fine and coarse sand fractions, therefore, the POM was isolated from the fine and coarse sand fractions using an NaI (sodium iodide) solution with a specific gravity of 1.7 g cm^{-3}. Floating POM was then removed with a scoopula and disposable pipette. To remove residual NaI solution, the POM was rinsed with a minimum of 200 mL of deionized water on a vacuum filtration apparatus set with a No. 4 Whatman paper. No floating POM < 63 µm was observed in soil samples.

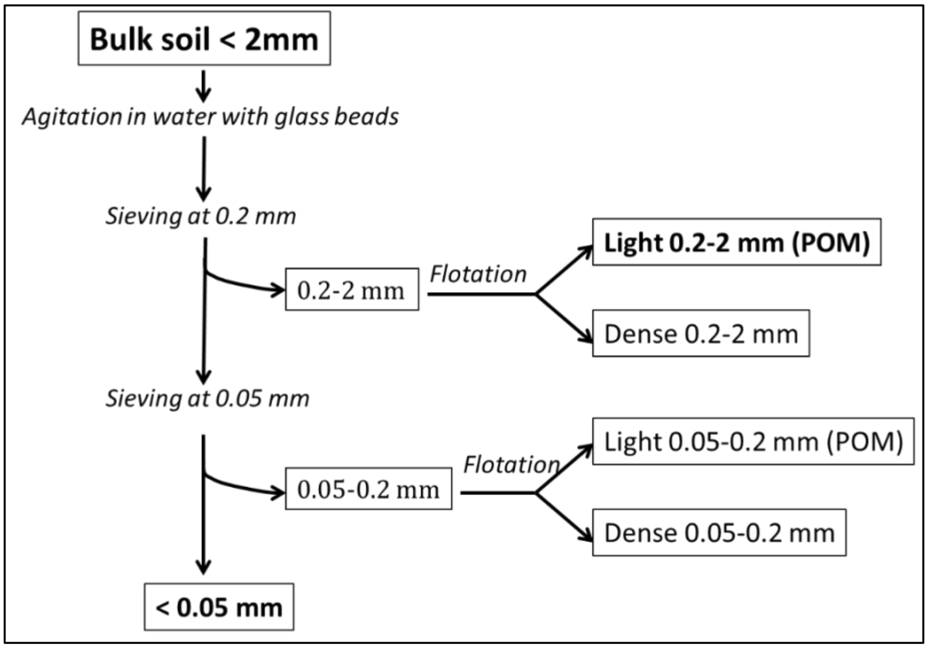


Figure 2.4. *Modified soil fraction procedure based on the Par + Den5 method described in Poeplau et al. 2018.*

Once soil mineral fractions and POM were separated, samples were oven-dried at 65°C in pre-weighed 1000 mL beakers until a constant weight was reached. Dried samples were finely ground using a mortar and pestle, then a subsample of each fraction (10-15 mg) was processed through an automated elemental analyzer (Thermo Scientific™ FlashSmart™) to determine the % carbon and nitrogen and C-N ratios. For ease of analysis, the silt and clay particles (< 63µm) were designated as the MAOM (Midwood et al. 2021) to compare against the POM fraction. Therefore, subsequent data analysis does not include the fine and coarse sand fraction. Please note that the isolation of the POM was not perfect, and there may have been some residual POM within the fine and coarse sand fractions.

Statistical Analysis

The statistical software R (R Core Team 2020) was used for data analysis, and the R package ggplot2 (Wickman 2016) was deployed to visualize data and produce figures. The alpha value for significance was set at α = .05.

Plant community structure, plant species diversity, biomass, and soil responses were compared between grazing treatments and the baseline (pre-treatment) data using the R package “lmer4” (Bates et al. 2015) for linear mixed effect models (LMMs). Each response variable was either square-root or log+1 transformed to meet the assumption of normality in the residuals, and this assumption was checked for each model by plotting the residuals and visually assessing their distribution. The LMMs used ‘treatment’ as the fixed effect and ‘year’ as the random effect. Given that each treatment had exactly one enclosure, spatial dependence between points within the same enclosure was captured in part by the fixed effect of treatment; including treatment (i.e. enclosure) in both fixed and random effects prevented model convergence, and thus the spatial relationship was left to the fixed components only. Furthermore, because the quadrats were randomly placed, there was no replication for individual sample locations. This reduced the spatial dependence between years, allowing time to be captured as the random effect of year, and space to be captured in the fixed effect of treatment. The R package “emmeans” (Lenth et al. 2022) was used to perform Tukey HSD post-hoc tests for pairwise comparisons between all groups. This was only applied for response variables where LMMs detected significant contrasts between the grazing treatment enclosures and baseline data.

Results

Plant Community Structure

All three types of grazing management appeared to influence the plant community at Drum Lake pasture (Table 2.3, Figure 2.5). Total grass cover increased within all treatment enclosures compared to baseline conditions, and doubled within the MiG enclosure from 19.1% at baseline to 38.7% after two years of grazing (Figure 2.5). The MiG and extensive grazing enclosures differed significantly from baseline native grass cover, where both values quadrupled (Table 2.3, Figure 2.5). The targeted enclosure also experienced a threefold increase in native grass cover (Table 2.3, Figure 2.5). Introduced grass cover did not differ between treatments, however extensive grazing demonstrated the lowest introduced grass cover at 0.6%, and MiG the greatest at 5.5%.

Total and native forb cover were greatest within the targeted grazing enclosure at 63.1% and 44.9%, respectively, whereas no differences were detected between the baseline, MiG, and extensive grazing treatments (Table 2.3, Figure 2.5). Introduced forb cover was greatest within the targeted enclosure at 18.3%. No significant differences in spotted knapweed cover were observed.

Soil crust and litter cover did not differ between grazing treatments; however, litter cover was the lowest within the targeted enclosure at 14%. Furthermore, bare ground cover decreased significantly within the targeted grazing enclosure when compared to the extensive and MiG enclosure (Table 2.3, Figure 2.5).

Table 2.3. *Summarized linear mixed effect models for the vegetation composition and ground cover response variables, including the transformed estimated means and standard error values. Significant contrasts (α = .05) between treatments are provided from Tukey HSD post-hoc tests.*

Response variable	Transformation	Treatment	Estimated Mean (transformed)	Standard error	Significant contrast
Grass Cover (%)					
Total	square root	Control	3.8	0.671	MiG
		MiG	6.14		Control
		TG	4.89	0.553	
		EG	5.69		-
Native	square root	Control	2.1	0.783	MiG; EG
		MiG	5.63		Control
		TG	4.51	0.625	-
		EG	5.6		Control
Introduced	log+1	Control	1.12	0.415	-
		MiG	0.98		-
		TG	0.82	0.368	-
		EG	0.19		-
Forb Cover (%)					
Total	square root	Control	5.43	0.331	TG
		MiG	4.88		TG
		TG	7.76	0.405	MiG; EG; Control
		EG	6.2		TG
Native	square root	Control	4.21	1.003	-
		MiG	3.19		TG
		TG	6.33	0.812	MiG
		EG	4.8		-
Introduced	square root	Control	3.1	0.293	-
		MiG	3.28		-
		TG	3.6	0.35	-
		EG	3.34		-
Spotted knapweed	log+1	Control	1.97	0.221	-
		MiG	1.95		-
		TG	2.07	0.243	-
		EG	1.97		-
Ground Parameters (%)					
Bare ground	log+1	Control	2.42	0.464	-
		MiG	2.27		TG
		TG	1.55	0.352	MiG; EG
		EG	2.27		TG
Crust	square root	Control	2.09	0.347	-
		MiG	2.52		-
		TG	1.67	0.343	-
		EG	2.74		-
Litter	square root	Control	3.96	0.197	-
		MiG	4.21		-
		TG	3.68	0.242	-
		EG	3.85		-

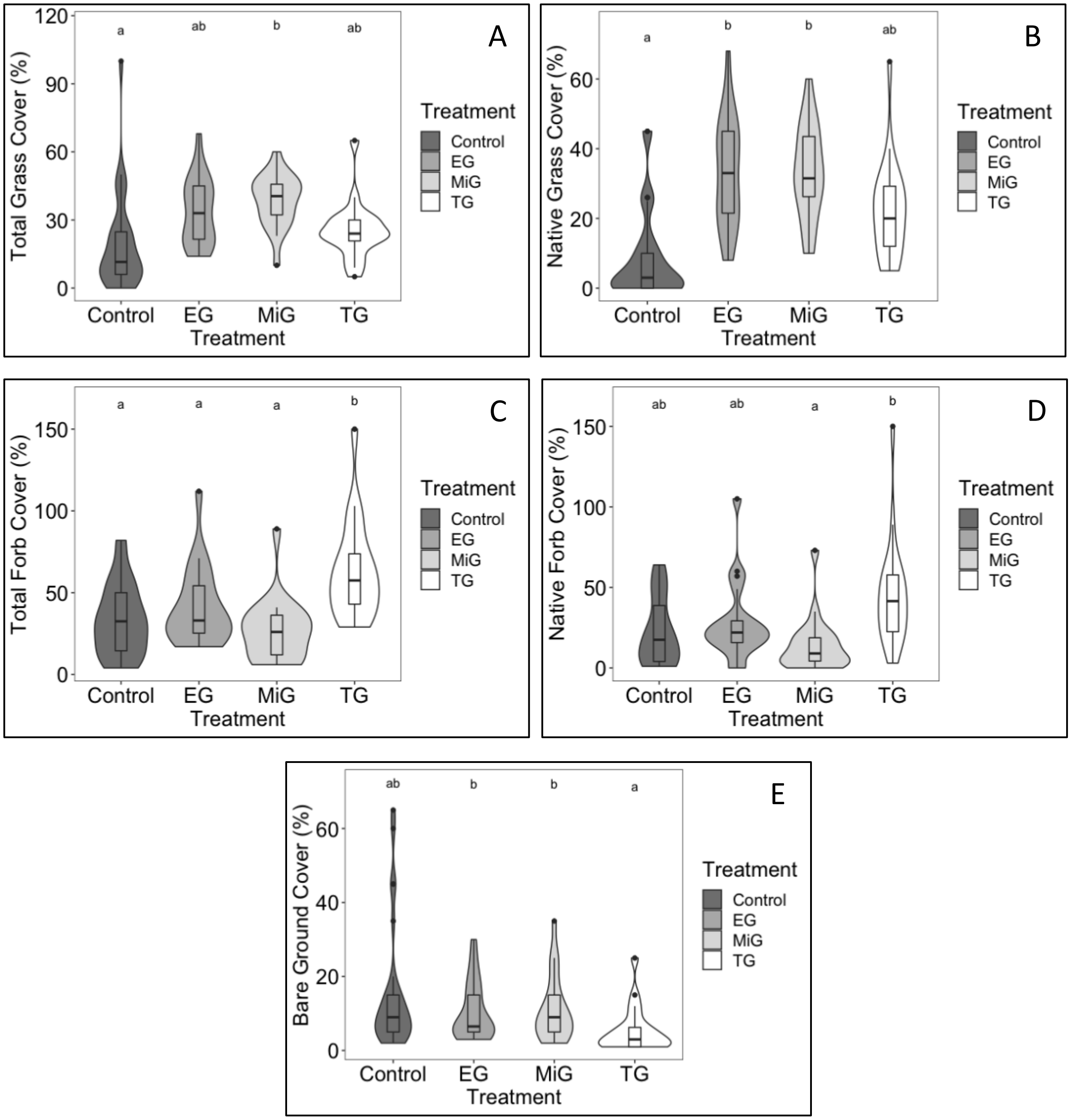


Figure 2.5. *Violin plots illustrating the untransformed (A) total grass, (B) native grass, (C) total forb, (D) native forb, and (E) bare ground percent cover data. Comparisons are made between the pre-treatment (control) data and the three grazing treatments after two years of treatments. Different letters between treatment denotes significance (α = .05) from Tukey HSD post-hoc tests.*

Diversity Indices

Shannon (H’) and Simpson (D) diversity increased amongst all grazing treatments when compared to the baseline data (Table 2.4). H’ and D diversity both increased significantly within the MiG and extensive grazing enclosures, whereas the targeted enclosure experienced a significant increase in H’ but did not differ from baseline for D diversity (Table 2.4, Figure 2.6).

Table 2.4. *Summarized linear mixed effect models for the Shannon (H’) and Simpson (D) diversity index response variables, including the transformed estimated means and standard error values. Significant contrasts (α = .05) between treatments are provided from Tukey HSD post-hoc tests.*

Response variable	**Transformation**	**Treatment**	**Estimated Mean (transformed)**	**Standard error**	**Significant contrast**
Diversity Index					
Shannon (H')	log+1	Control	0.803	0.022	MiG; TG; EG
		MiG	0.961		Control
		TG	0.949	0.027	Control
		EG	0.979		Control
Simpson (D)	log+1	Control	0.522	0.011	MiG; EG
		MiG	0.584		Control
		TG	0.562	0.013	-
		EG	0.584		Control

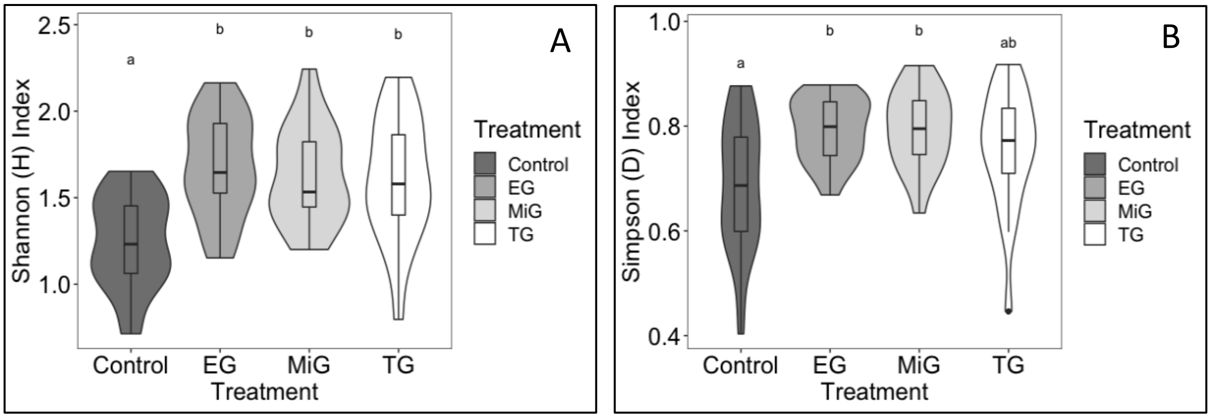


Figure 2.6. *Violin plots illustrating the untransformed (A) Shannon (H) diversity and, (B) Simpson (D) diversity. Comparisons are made between the pre-treatment (control) data and the three grazing treatments after two years of treatment. Different letters between treatment denotes significance (α = .05) from Tukey HSD post-hoc tests.*

Biomass

Biomass values varied by functional group and between grazing treatments. The targeted grazing enclosure displayed the greatest total live biomass, at 54.6 g/.25m^2, whereas the MiG and extensive enclosures contained similar values of 36.8 and 36.4 g/.25m^2, respectively (Table 2.5, Figure 2.7). The extensive enclosure had the lowest grass productivity at 14.4 g/.25m^2, whereas the MiG enclosure had the greatest at 21.3 g/.25m^2 (Table 2.5). Mixed forb productivity was greatest within the targeted enclosure, and the lowest within the MiG enclosure (Table 2.5, Figure 2.7). Spotted knapweed biomass did not vary between treatment enclosures. Litter biomass was greatest within the targeted enclosure, whereas the MiG and extensive enclosures contained approximately half the litter of the targeted enclosure (Table 2.5, Figure 2.7).

Table 2.5. *Summarized linear mixed effect model results for the biomass data, including the transformed estimated means and standard error values. Significant contrasts (α = .05) between treatments are provided from Tukey HSD post-hoc tests.*

Response variable	Transformation	Treatment	Estimated Mean (transformed)	Standard error	Significant contrast
Biomass (g/.25m^2)					
Mixed grasses	log + 1	MiG	3.03		EG
		TG	2.73	0.106	-
		EG	2.6		MiG
Mixed forbs	log + 1	MiG	1.33		TG; EG
		TG	2.82	0.231	MiG
		EG	2.36		MiG
Spotted knapweed	log + 1	MiG	1.5		-
		TG	2.28	0.409	-
		EG	1.58		-
Total live	log + 1	MiG	3.52		TG
		TG	3.94	0.154	EG; MiG
		EG	3.55		TG
Litter	log + 1	MiG	3.02		TG
		TG	3.63	0.132	EG; MiG
		EG	2.98		TG

The estimated biomass utilization values were greatest within the extensive and MiG enclosures, at 54.1 and 54.2%, respectively. The targeted enclosure experienced the lowest percent utilization at 33.5%.

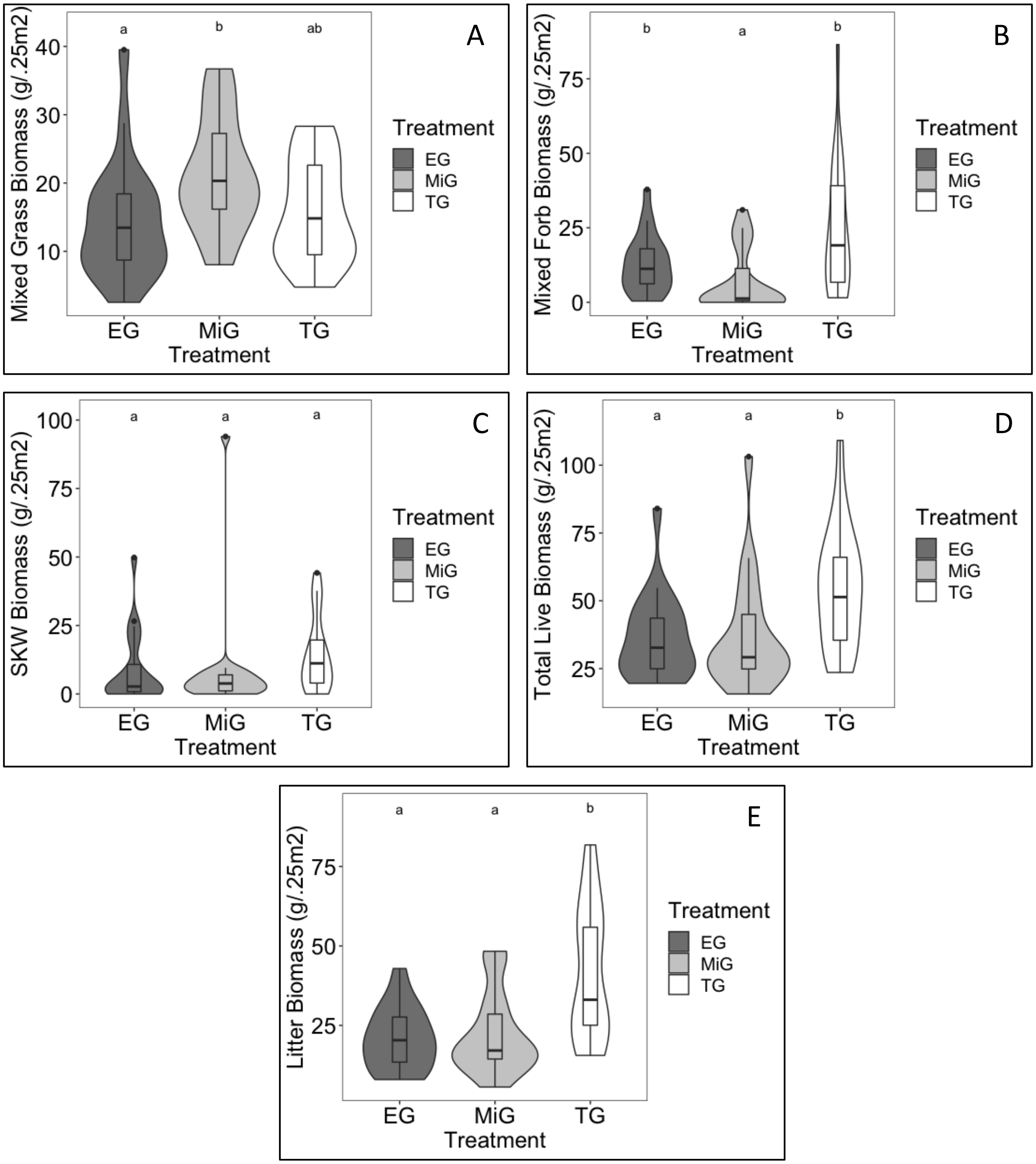


Figure 2.7.*Violin plots illustrating the untransformed (A) mixed grass, (B) mixed forb, (C) spotted knapweed (SKW), (D) total live, and (E) litter biomass expressed as g/.25m^2 in late July. Different letters between treatment denotes significance ($\alpha = .05$) from Tukey HSD post-hoc tests.*

Forage Nutritive Values

At the point of targeted grazing, *C. stoebe* appeared to contain more crude protein and total digestible nutrients (TDN) in late July than the graminoids did in late July and early September (Table 2.6). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) values were lower in spotted knapweed compared to the grasses (Table 2.6). In respect to nutrients, spotted knapweed contained more calcium, potassium, and iron than the grasses during the targeted grazing trial.

Table 2.6. *Descriptive summary of mean forage nutritive values (± stdv.) of graminoids in late July (point of targeted grazing treatment) and early September, and spotted knapweed in late July.*

		% Dry Matter									**Ppm**			
Plant Group	**Sampling Period**	ADF[1]	aNDF[2]	Ash	Ca	Crude Protein	K	Mg	P	TDN[3]	Cu	Fe	Mg	Zn
Graminoids	Late July	41.5	67.5	13.1	0.4	5.0	0.7	0.1	0.1	50.5	15.5	82.5	36.7	15.5
		(1.0)	(2.6)	(1.6)	(0.1)	(0.4)	(.1)	(.01)	(.02)	(1.3)	(0.8)	(34.2)	(3.4)	(1.8)
	Early September	44.3	69.0	6.7	0.4	4.2	0.4	0.1	0.1	54.8	2.7	102.3	44.8	14.2
		(1.1)	(2.0)	(1.2)	(0.1)	(0.5)	(.03)	(.02)	(.02)	(.5)	(0.8)	(17.4)	(13.0)	(2.3)
Spotted Knapweed	Late July	30.3	39.6	9.6	1.3	7.2	1.7	0.2	0.2	62.2	8.5	117.7	38.5	17
		(2.6)	(4.2)	(2.5)	(0.3)	(0.8)	(.26)	(.02)	(.02)	(3.1)	(1.0)	(41.5)	(9.5)	(1.4)

[1] Acid detergent fiber.

[2] Neutral detergent fiber.

[3] Total digestible nutrients.

Soil Bulk Density

After three years of grazing, no significant differences in bulk density between treatment groups were detected.

Soil pH

Soil pH was more acidic within the targeted enclosure compared to the MiG enclosure at both sampling depths (Figure 2.8), whereas pH values did not differ between MiG and extensive treatments in the 0-10 cm nor 10-20 cm sampling depths (Table 2.7, Figure 2.8).

Table 2.7. *Summarized linear mixed effect models for the soil pH and soil organic matter data at both sampling depths (0-10 and 10-20 cm), including the transformed estimated means and standard error values. Significant contrasts (α = .05) between treatments are provided from Tukey HSD post-hoc tests.*

Response variable	Transformation	Treatment	Estimated Mean (transformed)	Standard error	Significant contrast
pH					
0-10 cm	log + 1	MiG	2.07	0.0195	TG
		TG	2.04	0.0195	MiG; EG
		EG	2.07	0.0195	TG
10-20 cm	log + 1	MiG	2.07	0.0129	TG
		TG	2.05	0.0129	MiG
		EG	2.07	0.0129	-
Soil Organic Matter (SOM) %					
0-10 cm	log + 1	MiG	1.87	0.148	TG
		TG	2.17	0.148	EG; MiG
		EG	2	0.148	TG
10-20 cm	log + 1	MiG	1.67	0.141	-
		TG	1.71	0.141	EG
		EG	1.57	0.141	TG

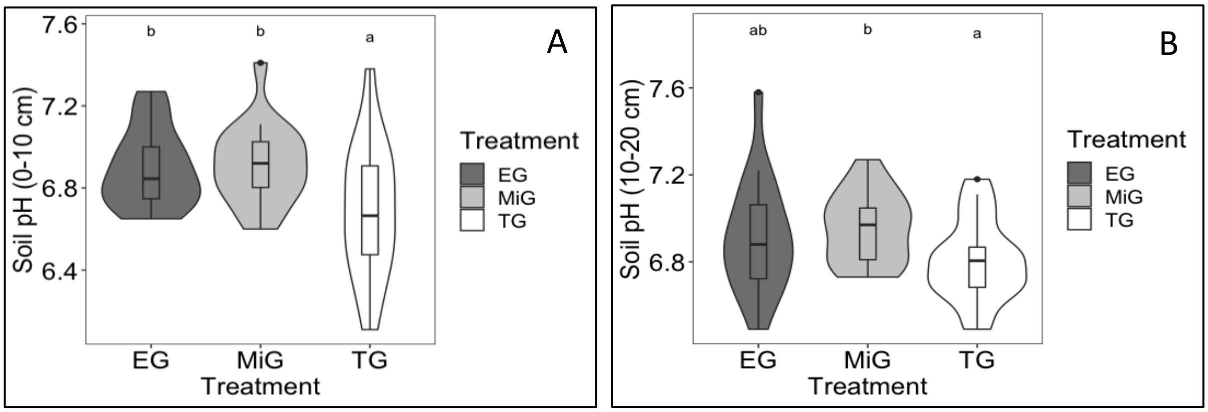


Figure 2.8.*Violin plots illustrating soil pH at the (A) 0-10 cm and (B) 10-20 cm sampling depths. Different letters between treatment denotes significance (α = .05) from Tukey HSD post-hoc tests.*

Soil Organic Matter (SOM)

Soil organic matter values ranged from 3.97% to 8.01 % within the top 20 cm of the soil profile (Table 2.7, Figure 2.9). The majority of SOM was measured within the upper 10 cm of soil (Table 2.7, Figure 2.9). At the 0-10 cm sampling depth, the MiG and extensive treatment enclosures contained less SOM than the targeted treatment (Table 2.7, Figure. 2.9). At the 10-20 cm sampling interval, the targeted enclosure contained more SOM than the extensive enclosure, but did not differ from the MiG enclosure (Table 2.7, Figure 2.9).

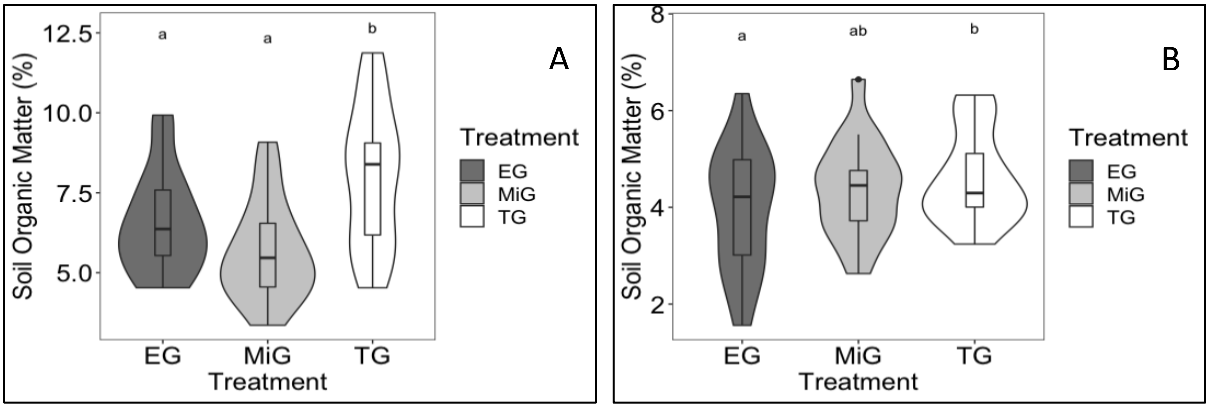


Figure 2.9. *Violin plots illustrating the percent soil organic matter data at the (A) 0-10 cm and (B) 10-20 cm sampling depths. Different letters between treatment denotes significance (α = .05) from Tukey HSD post-hoc tests.*

Soil Fractionation

No differences in POM carbon (C), nitrogen (N) or C-N ratio were detected between treatments at both soil sampling depths (Table 2.9). The majority of soil carbon was observed within the POM fraction and POM-C content did not appear to change with depth (Table 2.8). POM-N did not differ by grazing treatment, but did appear to decrease with depth (Table 2.8). The mean C-N ratio for the POM fraction varied between 14.1 to 17.3 within the top 20 cm of soil (Table 2.8).

The C and N within the MAOM fraction was greater within the targeted grazing enclosure at the 0 – 10 cm sampling depth (Table 2.8, Figure 2.10). No differences in soil C, N or C-N ratio were detected in the MAOM fraction at the 10 – 20 cm sampling depth (Table 2.8).

Table 2.8. *Summarized linear mixed effect model the soil carbon, nitrogen and C-N ratio for the particulate organic matter (POM) and mineral associated organic matter (MAOM) by treatment and soil sampling depth (0-10 or 10-20 cm). Significant contrasts (α = .05) between treatments are provided from Tukey HSD post-hoc tests.*

Response variable	Transformation	Treatment	Estimated Mean (transformed)	Standard error	Significant contrast
POM (0-10 cm)					
Carbon	Square root	MiG	4.52	0.109	-
		TG	4.73	0.109	-
		EG	4.59	0.109	-
Nitrogen	Square root	MiG	1.2	0.045	-
		TG	1.26	0.045	-
		EG	1.22	0.045	-
C-N Ratio	Square root	MiG	3.78	0.064	-
		TG	3.75	0.064	-
		EG	3.77	0.064	-
POM (10-20 cm)					
Carbon	Square root	MiG	4.52	0.103	-
		TG	4.6	0.103	-
		EG	4.47	0.103	-
Nitrogen	Square root	MiG	1.09	0.022	-
		TG	1.14	0.022	-
		EG	1.13	0.022	-
C-N Ratio	Square root	MiG	4.16	0.066	-
		TG	4.05	0.066	-
		EG	3.95	0.066	-
MAOM (0-10 cm)					
Carbon	Square root	MiG	1.69	0.064	TG
		TG	1.89	0.064	EG; MiG
		EG	1.7	0.064	TG
Nitrogen	Square root	MiG	0.553	0.069	TG
		TG	0.623	0.069	EG; MiG
		EG	0.554	0.069	TG
C-N Ratio	Square root	MiG	3.08	0.266	-
		TG	3.07	0.266	-
		EG	3.1	0.266	-
MAOM (10-20 cm)					
Carbon	Square root	MiG	1.49	0.048	-
		TG	1.48	0.048	-
		EG	1.4	0.048	-
Nitrogen	Square root	MiG	0.46	0.034	-
		TG	0.48	0.034	-
		EG	0.446	0.034	-
C-N Ratio	Square root	MiG	3.25	0.156	-
		TG	3.1	0.156	-
		EG	3.15	0.156	-

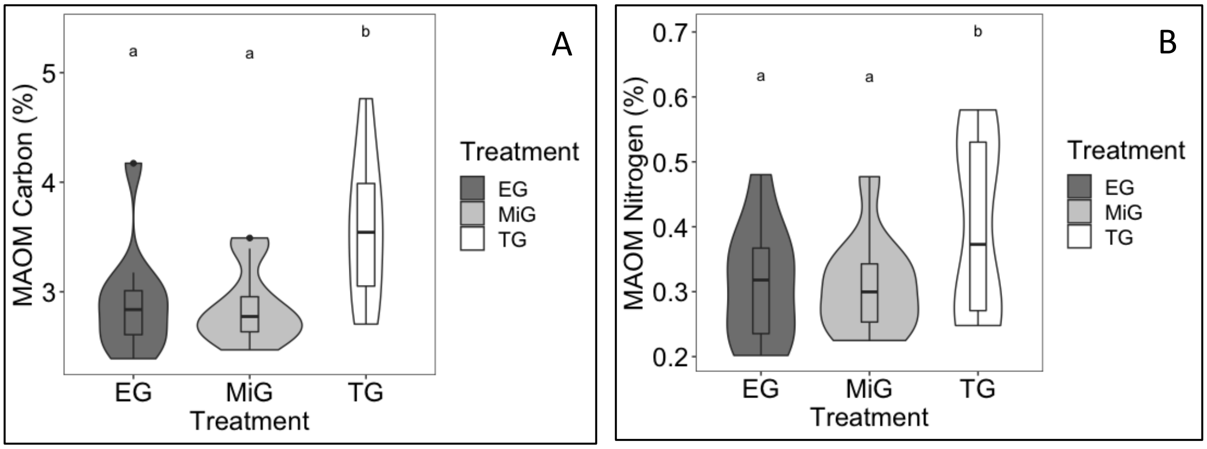


Figure 2.10. *Violin plots illustrating the (A) % carbon and (B) % nitrogen content within the mineral associated organic matter (MAOM) at the 0-10 cm sampling depth interval. Different letters between treatment denotes significance (α = .05) from Tukey HSD post-hoc tests.*

DISCUSSION

The results provide partial support for the hypothesis that intensive grazing management practices would improve the condition of invaded, semi-arid rangelands.

Plant Community Composition and Diversity

The first prediction was that intensively-grazed pastures would demonstrate increased cover of native plant species and litter, increased productivity, reduced bare ground cover, and improved diversity indices when compared to extensive grazing. I also predicted that extensive grazing would exhibit greater introduced plant species cover.

Contrary to my first hypothesis, MiG and extensive treatments both experienced significant increases in native grass cover and improved diversity indices when compared to the baseline (pre-treatment) conditions. Increased native grass cover suggests an improvement in range condition, where their expansive root structures also help stabilize soil and increase organic matter (Burke et al. 1998; Lund 2007; Li et al. 2017; Teague et al. 2020). Furthermore, Shannon (H') and Simpson (D) diversity both increased within all grazing treatment enclosures when compared to baseline. I anticipated to see lower diversity within the extensive grazing enclosure because of the potential for repeated grazing of preferred forage plants and increased bare soil, however, the opposite was true. These results could be attributed to the year-long rest period in between grazing events or the timing of grazing.

It is well established that incorporating rest into rangeland management plans is critical for plant recovery following a disturbance or defoliation event, such as grazing (Sanderman et al. 2015; Augustine et al. 2020). A case study conducted in Colorado's shortgrass prairie found that postponing grazing for an entire growing season promoted the growth of key forage species, such as needle and thread grass (*Hesperostipa comata*) and western wheatgrass (*Pascopyrum smithii*) when compared to a deferment period of several weeks to months (Derner et al. 2022). Moreover, the timing of grazing may have impacted plant community responses to grazing. In this study, the MiG and extensive treatments were conducted in mid-September; at this point, all preferred perennial bunchgrasses were dormant, had set seeds, and were not as vulnerable to defoliation when compared to the active growing period in the spring (Meays et al. 2014). Species, such as bluebunch wheatgrass (*Pseudoroegneria spicata*) and Junegrass (*Koeleria macrantha*), produce regrowth when summer temperatures drop and moisture increases in the fall (Wikeem et al. 1993). This is particularly relevant to my study in September 2019, where 59 mm of rainfall was observed. Therefore, these species may be able to exhibit valuable regrowth and recover more readily following a grazing event in mid-September.

With respect to the improved diversity indices amongst all treatments, Morris (2021) conducted a meta-analysis on the benefits and shortcomings of short-duration, moderate to high-intensity grazing and discovered that plant species richness generally increased compared to ungrazed areas. Moreover, the diversity and abundance of perennial grasses increased, more so than perennial forbs in response to forms of management-intensive grazing (Huruba et al. 2018; Morris 2021). That being said, overall species diversity and richness was generally unaffected within semi-arid rangeland environments (Olivia et al. 2021; Morris 2021). The improved diversity indices observed in this study could therefore be explained by the year-long grazing deferment, rather than the grazing treatment itself.

Species richness, or the number of unique species within an ecosystem, is also related to plant productivity (Grime 1973; Graham and Duda 2011; Fraser et al. 2015). The hump-backed model (Grime 1973) suggests that there is a unimodal relationship between plant productivity and species richness. Ecosystems that are drought-prone and contain fewer nutrients may experience lower plant productivity and a limited number of species adapted to those conditions (Grime 1973; Graham and Duda 2011; Fraser et al. 2015). Whereas the number of species within productive ecosystems may be limited by competitive effects (Graham and Duda 2011; Fraser et al. 2015). In this experiment, a combination of grazing and grazing deferment may have stimulated increased plant productivity, and, according to Grime's hump-backed model (1973), should therefore correspond with increased species richness and diversity.

The introduced grass cover within all treatment enclosures appeared to decrease when compared to baseline conditions, which is encouraging in respect to maintaining productive and preferred forage species. Introduced grasses, such Kentucky bluegrass (*Poa pratensis*), are a concern in rangelands because they have features that allow them to tolerate heavy grazing pressure, such as low growing points and the production of underground rhizomes (Meays et al. 2010). Cheatgrass (*Bromus tectorum*) also has an advantage in that it is an annual, it can germinate in the spring, summer, or fall, and it develops large, sharp awns when mature making it unpalatable for grazing animals (Mack 1981; Larson et al. 2017). The presence of these species highlights the importance of monitoring and adaptation when implementing a new grazing management strategy, and ensuring the percent cover of unwanted species does not increase over time.

The targeted grazing enclosure demonstrated the greatest total forb cover; however, the cover of native forbs did not significantly differ from baseline conditions. Two of the dominant native forbs on site, common yarrow (*Achillea millefolium*) and silky lupine (*Lupinus sericeus*) are characterized as 'increaser' species (Vesk and Westoby 2001; Gayton 2003). The term 'increaser' and 'decreaser' correspond to a plant's relative abundance or growth in response to increased grazing pressure (Vesk and Westoby 2001). Interestingly, I observed many grazed lupine and yarrow plants within the targeted enclosure (Figure 2.11). Lupines are known to be toxic to cattle when ingested in large quantities (Lee et al. 2020) and cattle generally tend to avoid grazing them (Lloyd 2019); therefore, I was surprised at the amount of native forb biomass removed on-site. It appeared that the cattle either grazed the native and non-native forbs selectively over the dormant grasses at the point of targeted grazing, or grazed the forbs because that was the most available type of forage within the targeted enclosure. Either way, the increased grazing pressure placed on the dominant forb species at the point of targeted grazing may have stimulated their growth and spread.

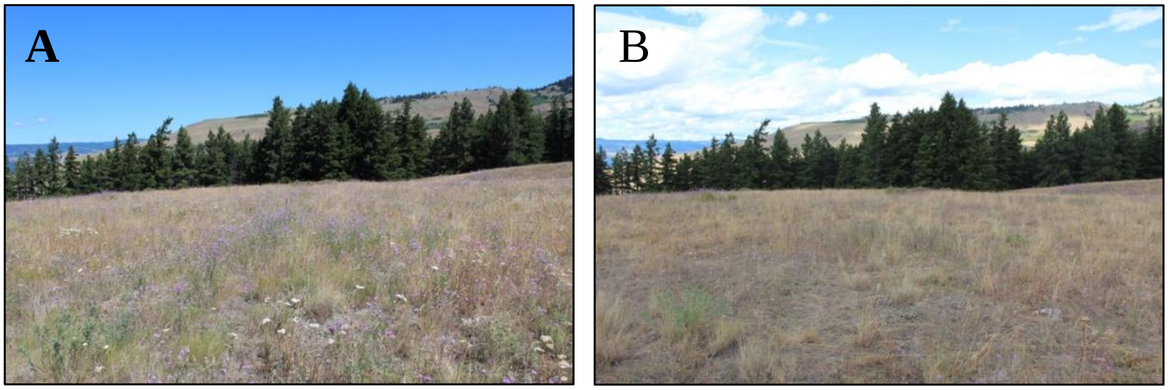


Figure 2.11. *A landscape view of the targeted grazing treatment enclosure before (A) and after (B) grazing at the late bud to flowering stage in early August, 2020.*

Neither litter nor biological crust cover differed between grazing treatments. However, bare ground cover was reduced within all three grazing treatments compared to baseline conditions. Bare ground is exposed soil that is unprotected by plant matter or organic materials, and can experience increased temperatures, decreased microbial activity, and increased erosion risk (Teague et al. 2011; Porensky et al. 2020). Research conducted by Teague et al. (2011) found that heavy, continuous season-long grazing increased bare ground, which can subsequently lead to nutrient leaching and increased opportunities for the establishment of invasive plant species, of which are often adapted to low nutrient and moisture conditions (Lee et al. 2014; Steanowicz et al. 2018; Fenetahun et al. 2021). Therefore, the reduction in bare ground observed in this study may help maintain or decrease soil temperatures, improve soil microbial activity, limit the amount of soil water being evaporated, and reduce the risk of plant invasion (Jefferson and Maxwell 2015; Porensky et al. 2020). I anticipated increased bare ground cover within the extensive grazing enclosure, however, the observation in this experiment may be associated with the prolonged period of rest and opportunity for plant establishment during active spring growth. If I had timed the grazing in the spring, I may have observed a different result.

Biomass

Grazing intensity refers to the amount of biomass or forage that has been removed during the grazing period (Wikeem and Wikeem 2004; Gardner et al. 2013). The estimated biomass utilization rates for the MiG and extensive enclosures were very similar at 54.1% and 54.2 %, respectively. The utilization rate exceeded the 'take half, leave half' rule of thumb for management-intensive grazing, which recommends 50% or more of aboveground biomass should remain post-grazing, otherwise above and below ground growth can become suppressed over time (Gerrish 2005). Interestingly, despite having the same stocking rate as the MiG treatment, the targeted enclosure exhibited a lower utilization rate of 33%. The targeted enclosure demonstrated a greater amount of live biomass; therefore, the cattle could have consumed equal amounts of biomass within the MiG and targeted enclosures, but the percent difference was not as great because more biomass existed in the targeted enclosure.

The total live, litter, and spotted knapweed biomass did not vary between the extensive and MiG treatments. However, the MiG enclosure demonstrated the greatest grass and the lowest forb biomass, whereas the opposite result was observed within the extensive enclosure. The cattle within the extensive enclosure had more time to revisit and re-graze preferred plants (Briske et al. 2008; Metera et al. 2010), that is the mixed grasses, at the point of grazing. The cattle within the MiG enclosure may have grazed more uniformly due to the short grazing duration and greater animal numbers (Conant et al. 2003). Stubble height measurements on the mixed grass and forb communities at the point of the MiG and extensive treatments would have provided a clearer description the grass versus forb use.

Total litter biomass was greatest within the targeted grazing enclosure. This result could be explained by the way litter biomass was collected, or because of the greater amount of total live biomass within the targeted enclosure. I combined the standing and ground litter together; therefore, dead-standing, woody knapweed stalks may have contributed more litter weight within the targeted enclosure.

It is important to note that biomass utilization, or the amount of forage eaten or trampled by grazing animals, is a difficult variable to accurately measure (Pauler et al. 2020; Jansen et al. 2021). Natural, semi-arid grasslands are among the most diverse grassland types in the world, and that diversity can be represented at very small spatial scales (Pauler et al. 2020). Variation in biomass productivity is, therefore, expected within these ecosystems. This variation, combined with our moderately-sized research pastures (50 m x 50 m) suggest that there may have been patches within each treatment enclosure that cattle selected more heavily than others. Consequently, the estimated utilization rates calculated in this chapter should be interpreted with caution.

Forage Nutritive Values

Spotted knapweed was originally believed to be an unpalatable species to grazing livestock (Griffith and Lacey 1991; Sheley and Jacobs 1997; Sheley et al. 1998). However, the results of this study demonstrate that, when grazed at the appropriate time, knapweed can be a valuable source of forage. This is due to the high crude protein and relatively low fibre values, findings which indicate good quality forage (Zhai et al. 2018). The results of this forage nutritive analysis are coincident findings from Kelsey and Mihalovich (1987), Olson et al. (1997), and Ganguli et al. (2010).

Targeted Cattle Grazing and Spotted Knapweed

The second hypothesis was that targeted cattle grazing would reduce the cover and productivity of the invasive plant, spotted knapweed (*Centaurea stoebe*). I found that the cover and productivity of spotted knapweed increased after two targeted grazing applications in late-July. Spotted knapweed cover nearly doubled compared to the baseline plant community, and productivity was also greatest within the targeted enclosure at 14.5g/.25m^2. It is therefore important to consider the compensatory growth effect, where plants will grow or increase in productivity in response to a disturbance or defoliation event, such as grazing (Kimball and Schiffman 2003). Compensatory growth is a common trait in invasive plant species, and is likely triggered by defoliation of the apical meristem or other disturbances (Müller-Schärer et al. 2004). Moreover, the compensatory growth of reproductive spotted knapweed stems has been reported after targeted sheep grazing (Olson et al. 1997), but overall grazing can still reduce knapweed dominance over time (Henderson et al. 2012; Mosley et al. 2016; Marchetto et al. 2021).

If my study was conducted over a longer time period, perhaps I would have seen a reduction in spotted knapweed cover and productivity. For instance, Mosley et al. (2016) observed an 86% reduction in spotted knapweed density over a four-year period using targeted sheep grazing in late-July. Furthermore, if my study was repeated with additional knapweed control measures, such as a fall herbicide application to target residual rosettes and ungrazed mature plants, we may also have seen a reduction plant density and productivity.

The forage nutrition analysis on spotted knapweed and the grasses at the point of targeted grazing may explain the selectivity of spotted knapweed observed (Figure 2.11). At this time, spotted knapweed is still actively growing, green and leafy, and therefore more palatable than the dormant perennial bunchgrasses. In the field we also observed many bunchgrasses that were either ungrazed or grazed minimally with sufficient residual biomass (Figure. 2.11).

These findings are similar to Henderson et al. (2018), where sheep appeared to prefer and select for spotted knapweed and avoid the dormant grasses.

In respect to a targeted grazing strategy, monitoring grazing intensity and adverse effects on the native plant community is very important. Fortunately, I did not observe significant reductions in native grass or native forb cover after two years of targeted grazing. However, to ensure there are no adverse effects on the native vegetation, future research should involve longer study periods (> 5) with annual monitoring before and after targeted grazing treatments. Other research opportunities include: mixed-species targeted grazing and integrating multiple rangeland restoration activities, such as seeding or re-vegetation post-grazing. Recommendations for spotted knapweed treatment followed by targeted grazing is discussed in Chapter 4, “Research Summary and Management Implications”.

Soil Responses to Grazing Management

Finally, I predicted that extensive grazing would increase soil bulk density and decrease soil organic matter, carbon, and nitrogen. Contrary to the hypothesis, both of the fall-grazed treatments, management-intensive and extensive grazing, appeared to exhibit similar responses to grazing when compared to targeted grazing.

No differences in soil bulk density were detected amongst the grazing treatments in this study, however, bulk density can increase in response to moderate to heavy grazing pressure (Chanasyk and Naeth 1995; Lee et al. 2014; Lai and Kumar 2020). A study conducted in Alberta’s foothill fescue grasslands found that an annual short-duration (1-week), heavy grazing period in mid-June increased soil bulk density by approximately 9% over four years (Chanasyk and Naeth 1995). In the fall, there is a tendency for greater soil moisture and precipitation within B.C.’s Southern Interior compared to mid-summer. Increased soil moisture and finer-textured soils may be attributed to increased bulk density during grazing periods (Laycock and Conrad 1967; Mayel et al. 2020). Finer-textured soil particles also display greater surface tension and can hold onto water more tightly, therefore soil is more easily compressed whereas dry soil requires much more force to become compacted (Chanasyk and Naeth 1995; Mayel et al. 2020). It is important to note that just five bulk density samples were collected within each treatment enclosure in this study. A greater sample size would have provided a more representative sample to compare against, and baseline samples would have allowed me to detect treatment effects more clearly.

Moreover, soil pH was more acidic within the targeted enclosure at both soil sampling depths (0-10 and 10-20 cm) when compared to the fall-grazed treatments. Soil pH can be influenced in several ways such as nitrogen additions (Lavallee et al. 2020) or the disruption or removal of topsoil in which the subsoil could be more alkaline (Evans et al. 2014). A global meta-analysis conducted by Lai and Kumar (2020) examined the influence grazing on soil pH and found that livestock manure and urine can generally increase soil pH. Without baseline soil data, however, it is difficult to interpret whether the decrease in soil pH was a result of the targeted grazing treatment, or whether the soil and composition of the parent material within the targeted enclosure is less alkaline than the other pastures.

Changes in soil organic matter, carbon, and nitrogen are likely associated with the changes in net primary productivity or biomass production (Conant et al. 2003). The results in this study demonstrate that the majority of SOM is located within the upper 10 cm of soil and that it decreases with depth. Plant productivity and SOM content was greatest within the targeted grazing enclosure. Moreover, SOM generally increases in response to the quantity and decomposition rate of plant litter (Ghorbani and Raiesi 2012; Teague et al. 2013; Lavallee et al. 2020). No significant difference in soil carbon, nitrogen or C-N ratio by grazing treatment were detected in this study, although POM was found to be the dominant form of carbon within the semi-arid rangeland soils. Midwood et al. (2021) detected similar results with natural grassland soils collected in the Okanagan region of B.C, where POM contributed 69% of the total carbon. This result could be attributed to climatic regime of the interior, semi-arid rangelands (Midwood et al. 2021). Furthermore, the C-N ratios within the MAOM fraction were much less than that of the POM fraction, which corresponds with findings from Cotrufo et al. (2019).

Mineral weathering processes are relatively slow within semi-arid environments when compared to irrigated agricultural pastures or pastures with higher soil moisture (Byrnes et al. 2018; Crème et al. 2020); therefore, the decomposition and storage of soil organic matter and soil carbon may become delayed. Interestingly, the MAOM C and N appeared to be greater within the targeted enclosure at the 0-10 cm sampling depth. MAOM is considered to be the more stable and protected form of carbon, where the turnover time or rate of microbial decomposition and process of sorption to the mineral-sized particles is very complicated and slow (Lavallee et al. 2020; Midwood et al. 2021). Additionally, no baseline soil data was collected, so it may be that the soil within the targeted enclosure simply exhibited different chemical properties.

Conclusions & Future Research

Overall, this study demonstrated that grazing can strongly influence the composition and productivity of plants in semi-arid environments. It is well documented that repeated grazing on preferred forages such as native bunchgrasses, can reduce plant vigor (Briske et al. 2008; Metera et al. 2010; Pauler et al. 2020). Therefore, it is also important to consider animal behaviour in this study. Cattle tend to be selective when grazing; their choices depend on forage availability, species distribution, and whether there are containment measures, such as fencing, in place (Pauler et al. 2020). The cattle used in this study were previously exposed to electric fencing, however, it is uncertain whether they had experienced being in small animal numbers, such as in the extensive grazing period. Moreover, changes in environmental or social conditions may influence animal behaviour and performance, specifically feed intake (Fraser 2004; Pauler et al. 2020). Efforts were made to minimize animal stress (providing water, ensuring sufficient forage was available, paired cattle/no isolated individuals), however it is unclear whether feeding behaviours would be altered within the 50 m x 50 m enclosures.

Furthermore, a mesic rangeland site may have experienced more pronounced vegetation responses to the grazing treatments used in this study (Teague et al. 2008; Booker et al. 2013). Greater moisture availability often equates to a more productive rangeland, whereas xeric sites, or those that experience minimal rainfall and sporadic growing seasons, generally have lower productivity (Teague et al. 2008). Therefore, Teague et al. (2008) posits that xeric or semi-arid pastures that are allowed longer periods of grazing deferment and plant recovery may not experience as pronounced benefits when grazing intensively when compared to a site with greater moisture availability. This experiment should therefore be repeated on a site with greater soil moisture.

In regard to the soil sampling, digging a soil pit within each enclosure and analyzing the profile would have been helpful to better understand the soil properties. This analysis also may have better explained the differences I observed in pH and MAOM C content. The short-term impacts of grazing management on belowground soil processes, such as microbial activity and decomposition rates, are also not very well understood within semi-arid rangelands (Whitehead 2020; Shrestha et al. 2020). Exploring microbial community assemblages and measuring the degree of weathering in these areas are important in our understanding of long-term soil carbon sequestration. Another variable that was not measured in this study was soil moisture. Soil moisture can influence the rate of organic matter decomposition, and is an important variable to consider when planning future soil carbon sequestration studies.

This study lacked replication of grazing treatments; therefore, this should be considered when interpreting results. However, with a limited timeline and only so many research assistants available, it was not feasible to conduct a replicate set of grazing pastures. Furthermore, baseline data, or data that was collected prior to the grazing manipulations, was not collected for soil properties or biomass data. It is therefore unclear whether the observed changes were a result of the grazing treatment or if differences in biomass or soil characteristics existed prior to the grazing manipulations (Bull et al. 2014). Despite these limitations, I was able to provide a thorough investigation of site characteristics and did the best I could with the resources I had.

In conclusion, it is important to consider that management-intensive grazing is complex and can require a great amount of labour and resources. For MiG to be successful, it is critical to adapt management practices in response to weather patterns, forage availability, and to the landscape or topography, among other factors (Savory and Parsons 1980; Dobb 2013; Mann and Sherren 2018; Augustine et al. 2020). Setting appropriate and achievable goals, practicing sound decision making, implementing thorough monitoring, and evaluating the success of management plans is key is MiG is to be successful within semi-arid rangeland environments (Savory and Parsons 1980; Mann and Sherren 2018; Derner et al. 2022).

REFERENCES

Abdalla M, Hastings A, Chadwick DR, Jones DL, Evans CD, Jones MB, Rees RM, Smith P. 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric Ecosyst Environ. 253(October 2017):62–81.

Alemu A, Kröbel R, McConkey B, Iwaasa A. 2019. Effect of increasing species diversity and grazing management on pasture productivity, animal performance, and soil carbon sequestration of re-established pasture in Canadian Prairie. Animals. 9(4):127.

Almeida RF, Queiroz IDS, Mikhael JER, Oliveira RC, Borges EN. 2019. Enriched animal manure as a source of phosphorus in sustainable agriculture. Int J Recycl Org Waste Agric. 8(s1):203–210.

Augustine DJ, Derner JD, Fernández-Giménez ME, Porensky LM, Wilmer H, Briske DD. 2020. Adaptive, multipaddock rotational grazing management: A ranch-scale assessment of effects on vegetation and livestock performance in semiarid rangeland. Rangel Ecol Manag. 73(6):796–810.

Bader BR, Taban SK, Fahmi AH, Abood MA, Hamdi GJ. 2021. Potassium availability in soil amended with organic matter and phosphorous fertiliser under water stress during maize (Zea mays L) growth. J Saudi Soc Agric Sci. 20(6):390–394.

Bates D, Mächler M, Bolker B, Walker S (2015). “Fitting Linear Mixed-Effects Models Using lme4.” *Journal of Statistical Software*, **67**(1), 1–48.

Bork EW, Döbert TF, Grenke JSJ, Carlyle CN, Cahill JF, Boyce MS. 2021. Comparative pasture management on Canadian cattle ranches with and without adaptive multipaddock grazing. Rangel Ecol Manag. 78:5–14.

Bradfield GE, Cumming WFP, Newman RF, Krzic M. 2021. Grazing exclosures reveal divergent patterns of change in bunchgrass grasslands of western Canada. Botany. 99(1):9–22.

Bull JW, Gordon A, Law EA, Suttle KB, Milner-Gulland EJ. 2014. Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. Conserv Biol. 28(3):799–809.

Burke IC, Laurenroth WK, Vinton MA, Hook PB, Kelly RH, Epstein HE, Aguiar MR, Robles MD, Aguilera MO, Murphy KL, et al. 1998. Plant-soil interactions in temperate grasslands. Biogeochemistry. 42:121–143.

Byrnes RC, Eastburn DJ, Tate KW, Roche LM. 2018. A global meta-analysis of grazing impacts on soil health indicators. J Environ Qual. 47(4):758–765.

Chanasyk DS, Naeth MA. 1995. Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. Can J Soil Sci. 75(4):551–557.

Chen W, Huang D, Liu N, Zhang Y, Badgery WB, Wang X, Shen Y. 2015. Improved grazing management may increase soil carbon sequestration in temperate steppe. Sci Rep. 5:1–13. doi:10.1038/srep10892.

Clements DR, Krannitz PG, Gillespie SM. 2007. Seed bank responses to grazing history by invasive and native plant species in a semi-desert shrub-steppe environment. Northwest Sci. 81(1):37–49.

Coffey L. 2007. Targeted Grazing: A Natural Approach to Vegetation Management and Landscape Enhancement. Launchbaugh KL, editor. Centennial, CO: American Sheep Industry Association.

Conant RT, Paustian K, Elliott ET. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl. 11(2):343–355.

Conant RT, Paustian K. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochem Cycles. 16(4):90-1-90–9.

Conant RT, Six J, Paustian K. 2003. Land use effects on soil carbon fractions in the southeastern United States. I. Management-intensive versus extensive grazing. Biol Fertil Soils. 38(6):386–392.

Cotrufo MF, Ranalli MG, Haddix ML, Six J, Lugato E. 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. Nat Geosci. 12(12):989–994. doi:10.1038/s41561-019-0484-6. http://dx.doi.org/10.1038/s41561-019-0484-6.

Crème A, Rumpel C, Malone SL, Saby NPA, Vaudour E, Decau M-L, Chabbi A. 2020. Monitoring grassland management effects on soil organic carbon—a matter of scale. Agronomy. 10(12):2016.

de Moraes Sá JC, Potma Gonçalves DR, Ferreira LA, Mishra U, Inagaki TM, Ferreira Furlan FJ, Moro RS, Floriani N, Briedis C, de Oliveira Ferreira A. 2018. Soil carbon fractions and biological activity based indices can be used to study the impact of land management and ecological successions. Ecol Indic. 84(January):96–105.

DiTomaso JM. 2000. Invasive weeds in rangelands: Species, impacts, and management. Weed Sci. 48(2):255–265.

Dobb, A. 2013. BC farm practices and climate change adaptation: management-intensive grazing. BC Agriculture and Food Climate Action Initiative. 22p.

Döbert TF, Bork EW, Apfelbaum S, Carlyle CN, Chang SX, Khatri-Chhetri U, Silva Sobrinho L, Thompson R, Boyce MS. 2021. Adaptive multi-paddock grazing improves water infiltration in Canadian grassland soils. Geoderma. 401(February).

[ECCC] Environment and Climate Change Canada. [Internet]. 2021. Historical data for Merritt, BC. Climate ID #1125073. www.climate.weather.gc.ca; [updated 2021 Nov 25].

Evans CRW, Krzic M, Broersma K, Thompson DJ. 2012. Long-term grazing effects on grassland soil properties in southern British Columbia. Can J Soil Sci. 92(4):685–693.

Fraser LH, Carlyle CN. 2011. Is spotted knapweed (*Centaurea stoebe* L.) patch size related to the effect on soil and vegetation properties? Plant Ecol. 212(6):975–983.

Ganguli AC, Hale MB, Launchbaugh KL. 2010. Seasonal change in nutrient composition of spotted knapweed and preference by sheep. Small Rumin Res. 89(1):47–50.

Gardner, W., M. Khadka and V. Volpatti. 2013. The grazing response index project. Agriculture and Agri-Food Canada. Kelowna, BC: Thompson Rivers University, 39 pp.

Gayton D V. 2003. British Columbia grasslands: Monitoring vegetation change. FORREX–Forest Research Extension Partnership, Kamloops, B.C. FORREX Series 7.
Gayton D, Miller V. 2012. Impact of biological control on two knapweed species in British Columbia. Ecosyst Manag. 13(3):1–14.

Graham JH, Duda JJ. 2011. The humpbacked species richness-curve: A contingent rule for community ecology. Int J Ecol. 2011(Figure 1). doi:10.1155/2011/868426.

Griffith D, Lacey JR. 1991. Economic evaluation of spotted knapweed (*Centaurea maculosa*) control using picloram. J Range Manag. 44(1):43. doi:10.2307/4002636.

Grime JP. 1973. Competitive exclusion in herbaceous vegetation. Nature. 242:344–347.

Gupta KK, Aneja KR, Rana D. 2016. Current status of cow dung as a bioresource for sustainable development. Bioresour Bioprocess. 3(1).

Henderson SL, Mosley TK, Mosley JC, Kott RW. 2012. Spotted knapweed utilization by sequential cattle and sheep grazing. Source Rangel Ecol Manag. 65(3):286–291.

Hewins DB, Lyseng MP, Schoderbek DF, Alexander M, Willms WD, Carlyle CN, Chang SX, Bork EW. 2018. Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Sci Rep. 8(1):1–9.

Hobbs RJ, Huenneke LF. 1992. Disturbance, diversity, and invasion: implications for conservation. Conserv Biol. 6(3):324–337. doi:10.1046/j.1523-1739.1992.06030324.x.

Iverson K. 2004. Grasslands of the southern interior. Victoria, BC: Ministry of Sustainable Resource Management. 6p.

Jansen V, Traynor ACE, Karl JW, Lepak N, Sprinkle J. 2021. Monitoring grazing use: Strategies for leveraging technology and adapting to variability. Rangelands. 44(1):64–77.

Jefferson J, Maxwell R. 2015. Evaluation of simple to complex parameterizations of bare ground evaporation. J Adv Model Earth Syst. 7:1075–1092.

Kimball S, Schiffman PM. 2003. Differing effects of cattle grazing on native and alien plants. Conserv Biol. 17(6):1681–1693.

Klinkenberg, Brian. (Editor) 2021. E-Flora BC: Electronic atlas of the flora of British Columbia [eflora.bc.ca]. Lab for Advanced Spatial Analysis, Department of Geography, University of British Columbia, Vancouver.

Krzic M, Naugler T, Dyanatkar S, and Crowley C. 2010. Virtual soil lab modules. University of British Columbia (UBC), Vancouver.

Krzic M, Lamagna SF, Newman RF, Bradfield G, Wallace BM. 2014. Long-term grazing effects on rough fescue grassland soils in southern British Columbia. Can J Soil Sci. 94(3):337–345.

Lai L, Kumar S. 2020. A global meta-analysis of livestock grazing impacts on soil properties. PLoS One. 15(8):e0236638.

Lal R. 2009. Challenges and opportunities in soil organic matter research. Eur J Soil Sci. 60(2):158–169.

Larson CD, Lehnhoff EA, Rew LJ. 2017. A warmer and drier climate in the northern sagebrush biome does not promote cheatgrass invasion or change its response to fire. Oecologia. 185(4):763–774.

Lavallee JM, Soong JL, Cotrufo MF. 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob Chang Biol. 26(1):261–273.

Lavallee JM, Soong JL, Cotrufo MF. 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob Chang Biol. 26(1):261–273. doi:10.1111/gcb.14859.

Laycock WA, Conrad PW. 1967. Effect of grazing on soil compaction as measured by bulk density on a high elevation cattle range. J Range Manag. 20(3):136.

Lee RN, Bradfield GE, Krzic M, Newman RF, Cumming WFP. 2014. Plant community – Soil relationships in a topographically diverse grassland in southern interior British Columbia, Canada. Botany. 92(11):837–845.

Lee ST, Welch KD, Stonecipher CA, Cook D, Gardner DR, Pfister JA. 2020. Analysis of rumen contents and ocular fluid for toxic alkaloids from goats and cows dosed larkspur (*Delphinium barbeyi*), lupine (*Lupinus leucophyllus*), and death camas (*Zigadenus paniculatus*). Toxicon. 176(November 2019):21–29.

Lenth RV, Buerkner P, Herve M, Jung M, Love J, Miguez F, Riebl H, Signmann H. 2022. emmeans: Estimated marginal means, aka least-squares means. R package version 2022.07.1. https://CRAN.R-project.org/package=emmeans

Li W, Xu F, Zheng S, Taube F, Bai Y. 2017. Patterns and thresholds of grazing-induced changes in community structure and ecosystem functioning: species-level responses and the critical role of species traits. J Appl Ecol. 54(3):963–975.

Li J, Ramirez GH, Kiani M, Quideau S, Smith E, Janzen H, Larney F, Puurveen D. 2018. Soil organic matter dynamics in long-term temperate agroecosystems: Rotation and nutrient addition effects. Can J Soil Sci. 98(2):232–245. doi:10.1139/cjss-2017-0127.

Lloyd D, Iverson K, Mackenzie K, Richardson H, Jeffries L. 2019. Laurie Guichon Memorial Grasslands Interpretive Site: A Baseline Inventory. Kamloops, BC. Grassland Conservation Council of British Columbia. 98 p.

Lund GH. 2007. Accounting for the world’s rangelands. Rangelands. 29 (1):3–10.

Mack RN. 1981. Invasion of *Bromus tectorum* L. into Western North America: An ecological chronicle. Agro-Ecosystems. 7(2):145–165.

Mann C, Sherren K. 2018. Holistic Management and adaptive grazing: A trainers’ view. Sustain. 10(6).

Maire J, Gibson-Poole S, Cowan N, Reay DS, Richards KG, Skiba U, Rees RM, Lanigan GJ. 2018. Identifying urine patches on intensively managed grassland using aerial imagery captured from remotely piloted aircraft systems. Front Sustain Food Syst. 2(April):1–11.

Marchetto KM, Wolf TM, Larkin DJ. 2021. The effectiveness of using targeted grazing for vegetation management: a meta-analysis. Restor Ecol. 1-12.

Mayel S, Jarrah M, Kuka K. 2021. How does grassland management affect physical and biochemical properties of temperate grassland soils? A review study. Grass Forage Sci. 76(2):215–244. doi:10.1111/gfs.12512.

Meays CL, Laliberte AS, Doescher PS. 2000. Defoliation response of bluebunch wheatgrass and crested wheatgrass: Why we cannot graze these two species in the same manner. Rangelands. 22(6):6–8.

Metera E, Sakowski T, Słoniewski K, Romanowicz B. 2010. Grazing as a tool to maintain biodiversity of grassland - a review. Anim Sci Pap Reports. 28(4):315–334.

Midwood AJ, Hannam KD, Gebretsadikan T, Emde D, Jones MD. 2021. Storage of soil carbon as particulate and mineral associated organic matter in irrigated woody perennial crops. Geoderma. 403:115185.

Mohammadi K, Heidari G, Khalesro S, Sohrabi Y. 2011. Soil management, microorganisms and organic matter interactions: A review. African J Biotechnol. 10(86):19840–19849.

Mosley JC, Frost RA, Roeder BL, Mosley TK, Marks G. 2016. Combined herbivory by targeted sheep grazing and biological control insects to suppress spotted knapweed (*Centaurea stoebe*). Invasive Plant Sci Manag. 9(1):22–32.

Müller-Schärer H, Schaffner U, Steinger T. 2004. Evolution in invasive plants: Implications for biological control. Trends Ecol Evol. 19(8):417–422.

Nag, A. 2015. Analytical and instrumental techniques in agriculture, environmental and food engineering. Delhi, India: PHI Learning. 267p.

Newman R, Krzic M, Wallace B. 2011. Linking range health assessment methodology with science rough fescue grasslands of British Columbia. Victoria, BC.

Olson BE, Wallander RT, Lacey JR, Olson BE, Wallander RT, Lacey JR. 1997. Effects of sheep grazing on a spotted knapweed-infested Idaho fescue community. 50(4):386–390.

Palit R, Gramig G, Dekeyser ES. 2021. Kentucky bluegrass invasion in the northern great plains and prospective management approaches to mitigate its spread. Plants. 10(4):1–14.

Pavlů V, Hejcman M, Pavlů L, Gaisler J, Nežerková P. 2006. Effect of continuous grazing on forage quality, quantity and animal performance. Agric Ecosyst Environ. 113(1–4):349–355.

Pauler CM, Isselstein J, Suter M, Berard J, Braunbeck T, Schneider MK. 2020. Choosy grazers: Influence of plant traits on forage selection by three cattle breeds. Funct Ecol. 34(5):980–992.

Poeplau C, Don A, Six J, Kaiser M, Benbi D, Chenu C, Cotrufo MF, Derrien D, Gioacchini P, Grand S, et al. 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils – A comprehensive method comparison. Soil Biol Biochem. 125(April):10–26.

Porensky LM, McGee R, Pellatz DW. 2020. Long-term grazing removal increased invasion and reduced native plant abundance and diversity in a sagebrush grassland. Glob Ecol Conserv. 24:e01267.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.R-project.org/.

Raiesi F, Asadi E. 2006. Soil microbial activity and litter turnover in native grazed and ungrazed rangelands in a semiarid ecosystem. Biol Fertil Soils. 43(1):76–82.

Reeder JD and Schuman GE. 2002. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environmental Pollution 116:457- 463.

Rhodes AC, Rutledge J, DuPont B, Plowes RM, Gilbert LE. 2021. Targeted grazing of an invasive grass improves outcomes for native plant communities and wildlife habitat. Rangel Ecol Manag. 75(January):41–50.

Richardson H. 2015. A comparison of random forests and linear stepwise regressions to model and map soil carbon in south-central British Columbia grasslands using normalized difference vegetation index based models. Thompson Rivers University.

Sanderman J, Reseigh J, Wurst M, Young MA, Austin J. 2015. Impacts of rotational grazing on soil carbon in native grass-based pastures in southern Australia. PLoS One. 10(8):1–15.

Savory A, Parsons SD. 1980. The Savory Grazing Method. Rangelands. 2(6):234–237.

Sheley RL, Jacobs JS. 1997. “Acceptable” levels of spotted knapweed (*Centaurea maculosa*) control. Weed Technol. 11(2):363–368.

Sheley RL, Jacobs JS, Carpinelli MF. 1998. Distribution, biology, and management of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). Weed Technol. 12(2):353–362.

Shrestha BM, Bork EW, Chang SX, Carlyle CN, Ma Z, Döbert TF, Kaliaskar D, Boyce MS. 2020. Adaptive multi-paddock grazing lowers soil greenhouse gas emission potential by altering extracellular enzyme activity. Agronomy. 10(11):1781.

Smith P, Cotrufo MF, Rumpel C, Paustian K, Kuikman PJ, Elliott JA, McDowell R, Griffiths RI, Asakawa S, Bustamante M, et al. 2015. Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil. 1(2):665–685.

Stefanowicz AM, Majewska ML, Stanek M, Nobis M, Zubek S. 2018. Differential influence of four invasive plant species on soil physicochemical properties in a pot experiment. J Soils Sediments. 18(4):1409–1423.

Surber LMM, Rude ME, Roeder BL, Mosley TK, Grove A V., Walker JW, Kott RW. 2011. Percent spotted knapweed (*Centaurea stoebe*) in the diets of grazing sheep. Invasive Plant Sci Manag. 4(1):95–101.

Teague WR, Dowhower SL, Baker SA, Haile N, DeLaune PB, Conover DM. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric Ecosyst Environ. 141(3–4):310–322.

Teague R, Provenza F, Kreuter U, Steffens T, Barnes M. 2013. Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? J Environ Manage. 128:699–717.

Teague R, Kreuter U. 2020. Managing Grazing to Restore Soil Health, Ecosystem Function, and Ecosystem Services. Front Sustain Food Syst. 4(September):1–13.
Thrift BD, Mosley JC, Brewer TK, Roeder BL, Olson BE, Kott RW. 2008. Prescribed sheep grazing to suppress spotted knapweed on foothill rangeland. Rangel Ecol Manag. 61(1):18–25.

Tiscornia G, Jaurena M, Baethgen W. 2019. Drivers, process, and consequences of native grassland degradation: Insights from a literature review and a survey in Río de la Plata grasslands. Agronomy. 9(5):8–12.

Vesk PA, Westoby M. 2001. Predicting plant species' responses to grazing. J Appl Ecol. 38(5):897–909.

Wang Q, Li Y, Wang Y. 2011. Optimizing the weight loss-on-ignition methodology to quantify organic and carbonate carbon of sediments from diverse sources. Environ Monit Assess. 174(1–4):241–257.

Wang X, Vandenbygaart AJ, McConkey BC. 2014. Land management history of Canadian grasslands and the impact on soil carbon storage. Rangel Ecol Manag. 67(4):333–343.

Whitehead D. 2020. Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands. Front Sustain Food Syst. 4(October):1–7. doi:10.3389/fsufs.2020.585913.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wikeem BM, Mclean A, Quinton D, Bawtree A. 1993. An overview of the forage resource and beef production on Crown land in British Columbia. Can J Anim Sci. 73(4):779–794.

Wikeem B, Wikeem S. 2004. The grasslands of British Columbia. Kamloops, BC: Grasslands Conservation Council of BC.

Witzgall K, Vidal A, Schubert DI, Höschen C, Schweizer SA, Buegger F, Pouteau V, Chenu C, Mueller CW. 2021. Particulate organic matter as a functional soil component for persistent soil organic carbon. Nat Commun. 12(1):1–10.

Wooley SC, Smith B, King C, Seastedt TR, Knochel DG (2011) The lesser of two weevils: physiological responses of spotted knapweed (*Centaurea stoebe*) to above- and belowground herbivory by *Larinus minutus* and *Cyphocleonus achates*. Biocontrol Sci Technol 21:153–170

Zhai X, Zhang Y, Wang K, Chen Q, Li S, Huang D. 2018. Grazing effects on the nutritive value of dominant species in steppe grasslands of northern China. BMC Ecol. 18(1):1–9.

3. CHAPTER 3

TESTING THE EFFICACY OF TARGETED CATTLE GRAZING TO SUPPRESS SPOTTED KNAPWEED (CENTAUREA STOEBE) IN SEMI-ARID RANGELANDS

Introduction

Spotted knapweed (*Centaurea stoebe*) is biennial to short-lived perennial plant, first introduced to British Columbia in 1893 through contaminated soil used as ship ballast (Sheley et al. 1998). Further introductions were made through contaminated alfalfa seed (Maddox 1982). First-year spotted knapweed plants form a leafy rosette and second-year plants ‘bolt’ then become reproductive, producing an average of 1,000 seeds that remain viable for up to eight years (Davis et. al 1993; Gayton and Miller 2012). In heavily infested areas, spotted knapweed seed density has been reported to be as high as 5,000 to 40,000 seeds m^2 (Schirman 1981; Sheley et al. 1998; Benzel et al. 2009). Furthermore, plants can grow up to 1.5 meters in height and live up to nine years (Boggs and Story 1987; Sheley et al. 1998), however, the average spotted knapweed lifespan is 3-5 years (Watson and Renny 1974; Boggs and Story 1987). Spotted knapweed spreads primarily by seed, yet they can also develop two to six lateral stems that produce numerous reproductive branches (Sheley et al. 1998; Martin et al. 2014).

Spotted knapweed has several features that give it a competitive advantage over native grassland species. Unlike their graminoid counterparts, spotted knapweed lacks extensive underground root structures (Figure 3.1)**.** Instead, knapweed has a large taproot that can access deeper soil water and nutrients

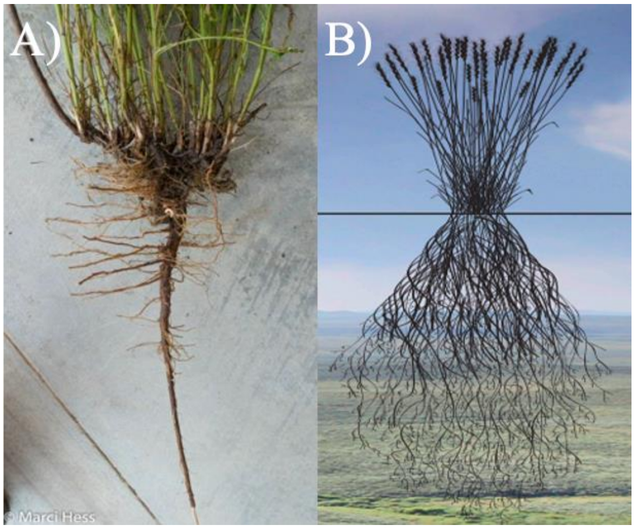


Figure 3.1. *Comparison of spotted knapweed's taproot and the fibrous root structure of bluebunch wheatgrass (Photo credits: Marci Hess and Sage Grouse Initiative).*

(Kelsey and Locken 1987), and reduce soil stability leading to erosion (Sheley et al. 1998; Rinella et al. 2001; Hook et al. 2004; Knochel et al. 2010). Fraser and Carlyle (2011) also discovered that large patches of spotted knapweed may uptake soil nitrogen and carbon at higher rates, therefore decreasing the availability of these elements for native plant species.

The effects of spotted knapweed invasion are felt province-wide, where its presence negatively impacts recreation values, wildlife habitat, and agricultural practices (Maxwell et al. 1992; Rinella et al. 2001; Gayton and Miller 2012; Lloyd et al. 2019). As of 2021, spotted knapweed is estimated to have infested 27,802 hectares of land in British Columbia (B.C.) (IAPP 2021). This estimate is very conservative, however, as the provincial Invasive Alien Plant Program (IAPP) may not capture infestation area data on private lands or locations with limited road access.

As a consequence of knapweed's rapid spread, B.C.'s agriculture producers are struggling with reduced pasture values (Benzel etl al. 2009; Magnin et al. 2016; Mosley et al. 2016) and the added expense and labour associated with chemical and mechanical control methods (Griffith and Lacey 1991; DiTomaso 2000; Marchetto et al. 2021). There are also limitations to which treatments can be applied based on the landscape type, climate, proximity to water, infestation size, and available resources. Therefore, to successfully restore an area infested with, and degraded by, spotted knapweed it's recommended to integrate a combination of treatment options, such as mechanical, cultural, chemical and biological controls (Sheley and Jacobs 1997; DiTomaso 2000; van Wilgen et al. 2001; Lake and Minteer 2018). Utilizing invasive plants as forage is becoming an increasingly popular and effective tool to help control invasive plants and limit their spread (Coffey 2007; Bohnert et al. 2014; Mosley et al. 2016; Rinella and Bellows 2016; Marchetto et al. 2021).

Targeted grazing involves developing specific vegetation management objectives, such as reduced invasive plant cover, then altering the duration, timing, and intensity of grazing to achieve those said objectives (Bailey et al. 2019; Marchetto et al. 2021). For instance, it's ideal to 'target' an invasive plant when it's most susceptible to defoliation, and at a time when the impacts on non-target species is minimal (Olson et al. 1997; Bailey et al. 2019).

Domestic livestock were originally believed to avoid spotted knapweed and it was considered poor quality forage (Harris and Cranston 1979; Maddox 1982; Kelsey and Mihalovich 1987; Kennett et al. 1992). This idea was supported by the fact that knapweed contains a bitter-tasting compound called cnicin that was believed to reduce the plants' palatability (Kelsey and Locken 1987; Ganguli et al. 2010). However, spotted knapweed is now recognized as nutritious forage (Thrift et al. 2008; Ganguli et al. 2010) and is comparable to that of native pasture and agronomic grasses (Burritt and Hart 2014).

Recent studies have found that sheep, goats, and cattle readily eat knapweed in all life stages (Henderson et al. 2012; Rinella and Bellows 2016; Ganguli et al. 2010). In Montana's bluebunch-fescue dominated rangeland, Thrift et al. (2008) achieved an average spotted knapweed utilization rate, or aboveground biomass removal, of 46% when grazed by sheep in July. Furthermore, research conducted by Henderson et al. (2012) found that grazing knapweed in late July during spotted knapweed's late bud to early flowering stage reduced the production of viable seeds by nearly 100%. The sheep and cattle used in the Henderson et al. (2012) study also appeared to prefer the knapweed over the grasses. Therefore, targeted cattle grazing has the potential to be an effective tool to help suppress spotted knapweed.

In theory, targeted cattle grazing could deplete knapweed growth and the soil seed bank, while also providing quality forage for cattle in mid to late summer. Grazing spotted knapweed at a point when it's susceptible to defoliation may also reduce its root mass (Olson et al. 1997), therefore depleting the plants' nutrient reserves over time.

When applying targeted grazing as an invasive plant management tool, it's important to consider the post-treatment effects, and next steps towards developing a range that's more resilient to invasion by non-native species. Gallandt (2006) recommends that rangeland invasive plant management strategies should be long-term, plant-specific, and integrate methods of depleting the weed seed bank.

Grazing can greatly influence the soil seed bank. For instance, seed banks can be depleted of their diversity and size as a result of heavy grazing (Soloman et al. 2005). Seed banks clearly play a critical role in restoration research, although the literature on soil seed bank composition in Western Canadian rangelands is limited, especially in response to targeted grazing strategies (Clements et al. 2007; Plue and Hermy 2012; Dobb and Burton 2013, Pyle 2018). Based on the existing literature, there is a need to develop management strategies to control spotted knapweed that also promote the restoration of native plant communities after knapweed treatment.

Research Objectives

There were two knowledge gaps I address in this study:

1) Will targeted cattle grazing help suppress the invasive plant spotted knapweed in B.C.'s native, semi-arid rangelands?

2) Can the existing soil seed bank help restore invaded, native plant communities in semi-arid rangeland following targeted grazing?

To address these knowledge gaps, I conducted a 9-week field experiment and a 16-week soil seed bank study in TRU's research greenhouse. The field experiment was conducted in the same location as described in Chapter 2. Therefore, no site description is included in Chapter 3.

First of all, I hypothesized that targeting spotted knapweed would reduce the number of seed heads and seeds produced when compared to the control, ungrazed plants. Secondly, targeted plants would exhibit lower above and belowground biomass in response to the grazing treatment. Lastly, there would be fewer spotted knapweed seeds observed within the targeted soil seed bank when compared to the control, ungrazed enclosure.

Materials and Methods

Field Experiment

In July 2019, two 50 x 50 m electric fence enclosures – one targeted and one ungrazed control – were constructed at Drum Lake Pasture (Figure 3.2). Prior to July 2019, enclosures were grazed under the 2017-2021 Chutter Ranch LTD. range use plan and followed a spring-fall grazing rotation (Table 3.1). Vegetation surveys conducted in late June 2020 demonstrated that the targeted and control enclosures exhibited similar spotted knapweed cover values at 16.5% and 16.1%, respectively (Appendix 3.1)

Table 3.1. *Description of the grazing schedule for Drum Lake pasture as outlined in the 2017 - 2021 RUP prepared by Chutter Ranch Ltd.*

	Even years	**Odd years**
Pasture name	Drum Lake	Drum Lake
Period of use	Sept 19 - 28	June 1 - 10
No. and class of livestock	500 C/C	500 C/C 20 Bulls

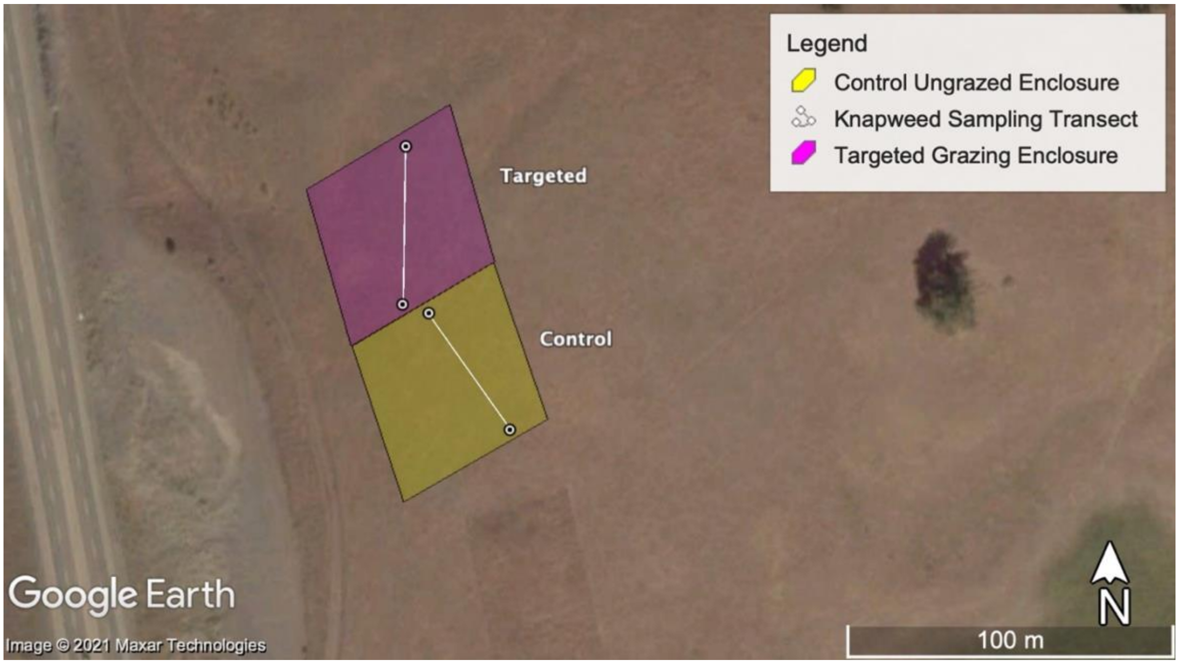


Figure 3.2. *Map illustrating the targeted (grazed) and control (ungrazed) treatment enclosures and knapweed sampling transects located at Drum Lake pasture in Merritt, BC.*

On August 4th, 2020 the targeted grazing enclosure was grazed at the height of spotted knapweed flowering by ten cow-calf pairs for a 24-hour period, equivalent to 0.8 animal unit months (AUMs) ha^{-1}. To help with distribution, cattle were supplied with four 40-gallon stock troughs filled with water, where one trough was placed in each corner of the enclosure.

Ethics Statement

This research was carried out under Thompson Rivers University Animal Care and Use Protocol No. 101899.

Spotted Knapweed Plant Traits & Response to Targeted Grazing

On June 22nd 2020, 20 single-stemmed and bolting spotted knapweed plants were selected in each treatment enclosure along two randomly-placed 50 m transects (Figure 3.2). Approximately every 2 meters, a knapweed plant closest to the transect was permanently tagged using a landscape pin with flagging tape. Field measurements were recorded weekly and included the number of buds and flowers and plant height. Plants were also monitored for regrowth, or the production of lateral stems and rosettes. All tagged knapweed plants were harvested on August 31st, prior to seed dispersal, by digging a hole deep enough to capture the taproot and carefully removing the entire plant. Plants were stored in paper bags, then brought to the Thompson Rivers University research greenhouse.

Harvested knapweed samples were oven-dried at 65°C for 48 hours and mass of the root and aboveground material was recorded on an analytical balance. The number of seed heads per plant were recorded, then seed heads were removed and stored at room temperature in paper bags until seeds could be counted. Knapweed seeds were sorted using a 10x magnification lens into the following categories: 1) mature (fully developed, black, hard seed coat), 2) immature (light brown or gray, hard seed coat), 3) doughy (soft seed coat, white or translucent) (Benzel et al. 2009), and 4) damaged seeds (Figure 3.3). Damaged seeds were identified by having evidence of feeding from biological control insects. In this study, doughy and damaged knapweed seeds were assumed to be unviable based on findings from Benzel et al. 2009.

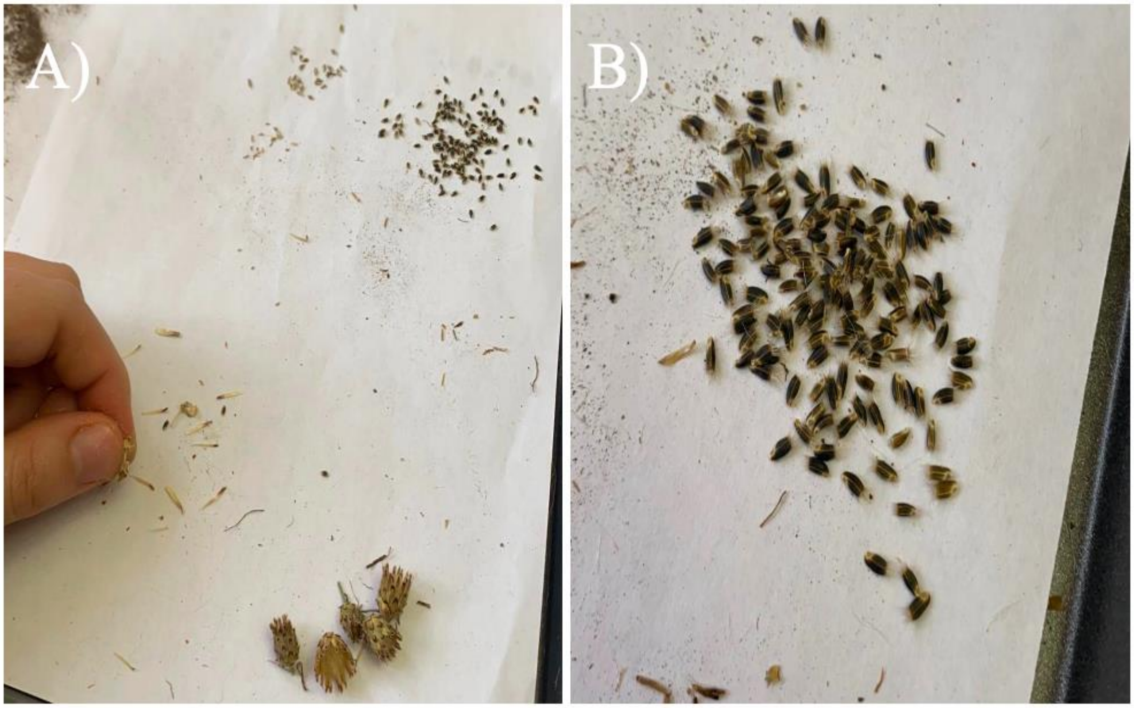


Figure 3.3. ***A)*** *Dissecting spotted knapweed seed heads and sorting the knapweed seeds by stages of maturity.* ***B)*** *A closer look at the mature spotted knapweed seeds collected.*

Soil Seed Bank Sampling

Soil seed bank sampling was conducted from September 28-30th, 2020. Within the 50 m by 50 m control and targeted grazing enclosures, twelve 1 m^2 quadrats were placed in a sampling grid (Figure 3.4). Within each 1 m^2 frame, twelve soil cores with a diameter of 5 cm and a depth of 5 cm (98.17 cm^3) were removed using a bulb planter. The soil cores within each 1m^2 quadrat were pooled to form a composite sample containing 1178 cm^3 or 1.178 L of soil, a total of approximately 14.14 L of soil per grazing enclosure (24 composite samples or

288 soil cores total). A buffer zone of two meters was maintained between the fence and the sampling grid to avoid edge effects.

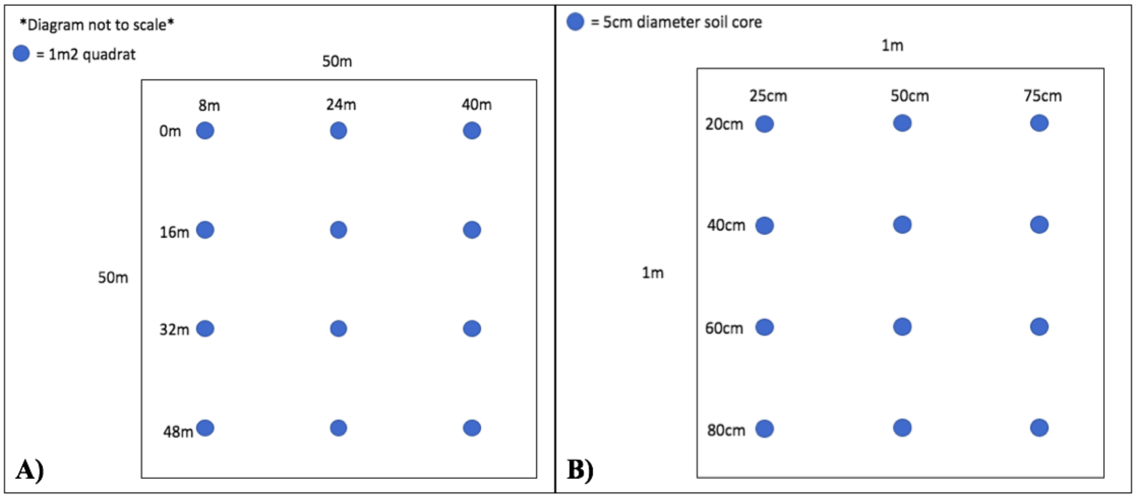


Figure 3.4. *Soil seed bank sampling design within each:* ***A)*** *50 m by 50 m treatment enclosure,* ***B)*** *1m^2 sampling quadrat frame.*

Greenhouse Study

Soil seed bank samples were placed in a chest freezer for three months to experience a cold stratification period, then grown in the greenhouse. Perforated germination trays (28 x 56 x 5.5 cm) were divided into two sections with landscaping fabric then filled with a 2 cm layer of sterile sand. Each composite soil sample was sieved with 4 mm mesh to remove rocks and plant materials, then spread out into a labeled germination tray; soil samples were allowed to air dry for two days prior to sieving. Samples were randomly assigned to a germination tray, then exposed to a 16-h day and 8-h night regime, a relative humidity of 30%, and a temperature setting of 20-25°C, as recommended by Plue and Hermy (2012).

Emerging seedlings were identified, counted, then removed (Figure 3.5). Unknown seedlings were transplanted into potting soil and left to grow until identification was possible. Rough and Idaho fescue seedlings were indistinguishable and were therefore grouped as ‘fescue species’. If no seeds germinated within a two-week period, the soil was gently turned over using a trowel. After 12 weeks, a 1% gibberellic acid solution was applied in an attempt to stimulate the growth of remaining, dormant seeds (Finkelstein et al. 2008). The greenhouse pod was monitored and maintained for external weed growth to prevent seeds from dispersing and contaminating the germination trays. The germination experiment was terminated after 16 weeks. Soil seed bank density was then calculated and converted to the number of seeds/m^2.

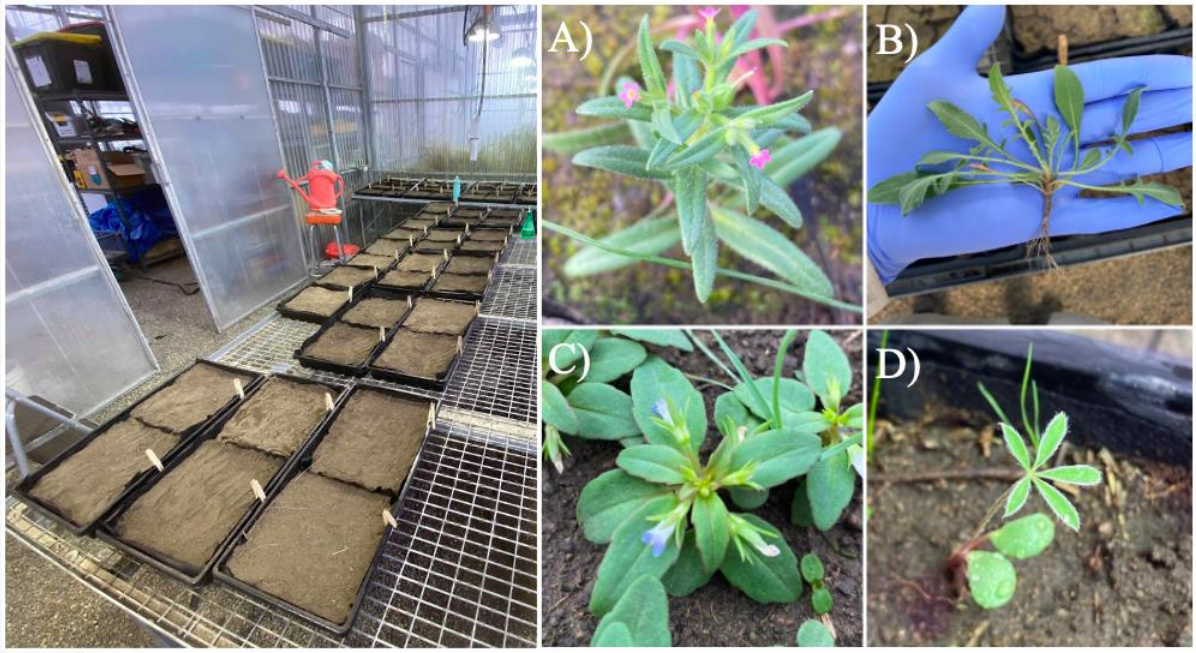


Figure 3.5. *The soil seed bank germination trays set up in the greenhouse, and a selection of seedlings identified in the seed germination experiment:* ***A)*** *Microsteris gracilis,* ***B)*** *Centaurea stoebe rosette,* ***C)*** *Collinsia parviflora and* ***D)*** *Lupinus sericeus.*

Statistical Analysis

Knapweed root and shoot weights were compared using independent samples T-test, where shoot weights had to be log transformed to meet normality and equal variance assumptions. Root-shoot ratio values did not meet the requirements for a parametric test following transformation attempts, therefore a non-parametric Mann-Whitney U test was used.

After transforming the raw data, the number of seed heads and the knapweed seeds at all stages of maturity (mature, intermediate, doughy, and damaged) did not pass the Shapiro-wilk tests for normality. Therefore, the non-parametric equivalent of an independent samples T-test, the Mann-Whitney U test was used to compare knapweed seed characteristics between the targeted and control plants.

Mean and standard error values presented in subsequent tables are from untransformed data.

Results

Spotted knapweed root weight passed passed the Shapiro-Wilks normality test (p = .382) and Levene's test of homogeneity of variances (p = .068). Log transformed knapweed shoot weight passed the Shapiro-Wilks normality test (p = .303) and Levene's test of homogeneity of variances (p = .112). For the remaining knapweed plant trait data, the Mann-Whitney U test statistics and significance values are summarized in Table 3.2.

Knapweed Response to Targeted Grazing

I observed that 75% of the tagged and targeted knapweed plants were grazed, where 10% of grazed plants exhibited regrowth, or the formation of one rosette post-grazing. Altogether, 185 knapweed seed heads were dissected and 2,456 knapweed seeds at all stages of maturity were counted (mature = 1,191; intermediate = 329; doughy = 734; damaged = 202).

Table 3.2. *Summarized mean spotted knapweed plant trait values (+/- 1 SE), in addition to the mean knapweed seeds (+/- 1 SE) grouped by seed maturity. Mann-Whitney U and independent sample t-test statistics are displayed. Bold p-values denote significance between the control and targeted knapweed plant variables (α = .05).*

	Mean +/- 1 SE			
Variable	**Targeted**	**Control**	**Statistic**	**p**
Seed Heads	1.5 ± .47	7.8 ± .73	U = 383.5	**<.001**
Shoot weight (g)	.93 ± .11	2.1 ± .24	T = -4.652	**<.001**
Root weight (g)	.48 ± .05	.54 ± .05	T = -.811	0.422
Root-shoot ratio	.57 ± .08	.29 ± .02	U = 63.5	**<.001**
Knapweed Seeds				
Mature	5.6 ± 2.97	54.0 ± 9.76	U = 376.0	**<.001**
Intermediate	1.5 ± .59	14.9 ± 3.12	U = 348.0	**<.001**
Doughy	5.1 ± 1.83	31.7 ± 3.73	U = 376.0	**<.001**
Damaged	1.4 ± .79	8.7 ± 1.41	U = 351.0	**<.001**

The targeted grazing treatment reduced the number of knapweed seed heads by over 80% (Table 3.2). Furthermore, knapweed shoot weight was reduced by 56% in the targeted plants respective to the control, ungrazed plants (Table 3.2). Before and after measurements displayed that an average of 12.9 cm of plant material (by height) was removed from the targeted plants as a result of the grazing treatment.

No differences were observed in the root mass between the targeted and control spotted knapweed plants (Table 3.2). Moreover, the root-shoot ratio was calculated to be smaller in the control plants compared to the targeted knapweed plants (Table 3.2).

Cattle readily consumed spotted knapweed in early August at the flowering stage and reduced the number of mature ($p < .001$) and intermediate ($p < .001$) seeds by 89.7 and 90% respective to control, ungrazed plants (Table 3.2).

Soil Seed Bank

Altogether, 740 seeds germinated and 17 species were detected in our sampling of the upper five centimeters of the soil seed bank (Table 3.3). Of those species, seven were introduced and ten were native to B.C.. The targeted and control enclosures had average seed densities of 1186 seeds/m^2 and 1304 seeds/m^2, respectively (Table 3.3).

Targeted grazing did not appear to reduce the number of spotted knapweed seeds in the seed bank, as samples contained an average of 153.1 seeds/m^2 compared to 146.1 seeds m/^{2} in the control enclosure (Table 3.3). Moreover, introduced plant species made up 32% of the targeted seed bank and 27% of the control, whereas the remaining 68% and 73% were native species.

Table 3.3. *Soil seed bank composition within the targeted and control enclosures at Drum Lake pasture. Species status, the total number of observed seedlings, and the average seed density (m^2) for each species is presented.*

Common name	Scientific name	Status	Total # seeds		Average seed density (m^2)	
			Targeted	Control	Targeted	Control
Cheatgrass	*Bromus tectorum*	Introduced	29	4	100.9	13.9
Fescue Species	*Festuca idahoensis* *Festuca campestris*	Native	56	86	194.8	299.2
Junegrass	*Koeleria macrantha*	Native	80	20	194.8	69.6
Kentucky bluegrass	*Poa pratensis*	Introduced	41	47	142.6	163.5
Sandberg's bluegrass	*Poa secunda spp secunda*	Native	58	16	201.8	55.7
Cut-leaved daisy	*Erigeron compositus**	Native	1	0	3.5	0
Holboell's rockcress	*Arabis holboellii*	Native	1	3	3.5	10.4
Silky lupine	*Lupinus sericeus*	Native	3	2	10.4	7.0
Slender phlox	*Microsteris gracilis*	Native	5	1	17.4	3.5
Small-flowered blue-eyed Mary	*Collinsia parviflora*	Native	36	142	125.2	494
Spotted knapweed	*Centauria stoebe*	Introduced	44	42	153.1	146.1
Spring draba	*Draba verna**	Native	2	0	7.0	0
Tall tumble mustard	*Sisymbrium altissimum**	Introduced	4	0	13.9	0
Western tansy mustard	*Descurainia sophia*	Introduced	1	3	3.5	10.4
Yarrow	*Achillea millefolium*	Native	3	0	10.4	0
Yellow alyssum	*Alyssum alyssoides*	Introduced	1	6	3.5	20.9
Yellow salsify	*Tragopogon dubius*	Introduced	0	3	0	10.4
Totals:	17 species		365	375	1186.3	1304.6

* Species that were not detected in vegetation surveys.

Junegrass, fescue species, Sandberg's bluegrass, Kentucky bluegrass, and spotted knapweed were the dominant species detected within the seed bank. Fescue was more dominant within the control enclosure, whereas Sandberg's and Junegrass were dominant within the targeted enclosure. Cheatgrass was also more prevalent within the targeted enclosure at 100.9 seeds/m^2 compared to just 13.9 seeds/m^2 in the control.

Discussion

This study demonstrated that targeted cattle grazing has the potential to suppress spotted knapweed growth and seed production within B.C.'s semi-arid rangelands. Our research findings were consistent with Rinella et al. (2001), Benzel et al. (2009), and Mosley et al. (2016), where one defoliation period during spotted knapweed's bud to flowering period is effective in reducing seed production. Mature spotted knapweed seeds are not formed until post-flowering (Watson and Kenny 1974), which at Drum Lake was observed in mid to late August. Despite this, a few individual knapweed plants may have been more advanced and matured earlier than others. Therefore, Wallander et al. (1995) and Benzel et. al (2009) recommend to quarantine livestock for 7 days after feeding on knapweed plants in full flower.

There is little, to no research on how the digestive tract of cattle influences knapweed seed viability. Wallander et al. (1995) fed rams, also a ruminant animal, approximately 5,000 mature spotted knapweed seeds and measured the recovery and viability of the seeds following digestion. They recovered 17% of the digested seeds, and percent viability ranged from 0-22% (Wallander et al. 1995). No viable seeds were detected two days after the knapweed seed feeding (Wallander et al. 1995). Therefore, the digestive tract of ruminant animals, such as sheep and cattle, have the potential to reduce the viability of mature spotted knapweed seeds. By repeating our experiment, cattle could be quarantined, and their manure collected, to observe whether knapweed seeds could be recovered. If seeds were detected within cattle manure, it's critical to test what percentage of the seeds would remain viable and for how long. That way, a more refined quarantine duration could be determined.

Furthermore, minimal regrowth was observed in the grazed spotted knapweed plants, with just 10% of the plants forming a rosette following grazing. Targeting spotted knapweed during mid-summer in semi-arid range makes plant recovery difficult (Mosley et al. 2016), as B.C.'s interior rangelands typically have very low soil moisture (Battigelli et al. 2003). In our experiment, knapweed plants could have been monitored into the fall when soil moisture increases, instead of being harvested in late August. This would have provided us with a clearer picture of knapweed survival and regrowth following targeted grazing.

With any targeted grazing strategy, it is important to ensure there are no adverse effects to the existing native plant community, wildlife, or to soil structure and function (Coffey 2007; Bailey et al. 2019; Marchetto et al. 2021). Future research should investigate the long-term effects of targeting spotted knapweed (> 5 years) on plant community dynamics, soil structure and function, and the soil seed bank.

It is also worth testing different types of livestock, as they exhibit different feeding preferences, forage intakes, and behaviours (Fraser 2004; Coffey 2017; Pauler et al. 2020). For instance, a study conducted in western Montana by Henderson et al. (2012) found that grazing with sheep and cattle sequentially suppressed spotted knapweed growth. Both animals also consumed more knapweed than grasses during spotted knapweed's late bud – early flowering stage (Henderson et al. 2012). Therefore, the timing of spotted knapweed defoliation, in addition to the type of grazing animal is important to consider.

It is well understood that cattle benefit from grazing taller forage plants; when forage plants are shorter, they are less accessible and we may begin to see reduced forage intake and body condition over time (Fraser 2004; Pauler et al. 2020). Spotted knapweed's rosette stage is leafy and palatable, but is also lower to the ground making this stage more difficult for cattle to graze. Whereas the later knapweed growth stages form woody, more fibrous stems that the cattle tend to avoid (Pauler et al. 2020). Whereas browsers, such as goats, can access shorter plants and they are better able to strip leaves from stems, and can easily chew and digest woody stems (Coffey 2007). Future research should apply multiple-species grazing in B.C.'s semi-arid rangeland, where two or more species of grazers are used (Coffey 2007).

This study also lacked replication, and should ideally be repeated in lower, middle and upper grassland sites. To do this, lower elevation grassland sites may need to be grazed earlier in the growing season due to warmer temperatures, less moisture, and more rapid plant growth and maturity (Wikeem and Wikeem 2004). A study investigating how spotted knapweed growth variables (including bud formation, flower development and seed set) vary by season and elevation would be very useful in our understanding of targeted grazing applications in B.C. rangelands.

Additionally, this study should be repeated in areas with varied degrees of infestation, for instance mild, moderate, and severe. Our study site had a relatively ‘light’ infestation (Thrift et al. 2008) of spotted knapweed, where the average percent cover amongst all pastures at Drum Lake was approximately 16%. It is important to determine whether targeted cattle grazing would be successful in areas with higher knapweed cover, or if favourable plant community shifts, such as improved cover of perennial bunchgrasses, would occur.

Soil Seed Bank

Targeted cattle grazing significantly reduced the number of seeds, at all stages of maturity, produced by spotted knapweed. However, knapweed seeds within the seed bank did not differ from the control, ungrazed enclosure. The results contradict Olson et al. (1997), where they observed more viable knapweed seeds within ungrazed areas than in the sheep-grazed areas after three consecutive summers of grazing. However, this study was limited in that the targeted enclosure was grazed for just one season. Ideally, this grazing experiment would continue for multiple years and be monitored frequently to determine if the knapweed seed bank would, in fact, also become depleted over time. Unfortunately, invasive plant suppression and removal is not a short-term project, and often requires many years of active treatment and management to achieve results. Based on the existing, literature, there is evidence to support that grazing will suppress the seed production of spotted knapweed over time (Olson et al. 1997; Thrift et al. 2008; Benzel et al. 2009; Henderson et al. 2012).

One reason that the targeted and control enclosure displayed similar seed densities could be that knapweed seeds have a long viability, up to seven years (Davis et. al 1993). There was also a presence of seed-feeding biological control insects (*Larinus minutus*) and knapweed seed head gall flies (*Urophora spp.*) on site, which may have contributed to a decline in knapweed seed numbers (Seastedt et al. 2007). Granivores, or small mammals and birds predating upon the knapweed seeds, could have also played a role in the knapweed seed densities seen in the experiment (Bernards and Morris 2017). Many seed caches of spotted knapweed were observed on site (Figure 3.6), and it brings to question the role of granivores and biological control insects in suppressing, or spreading, spotted knapweed seeds.

Figure 3.6. *Spotted knapweed seed caches, presumably formed from the small mammal population on site.*

Conclusions & The Future of Targeting Grazing

In conclusion, this research has demonstrated the effectiveness of targeted grazing in semi-arid rangelands. Integrating targeted grazing into rangeland weed management plans may help improve range condition and help create more productive, invasive free rangelands in B.C.'s Southern Interior.

Instead of complete knapweed eradication being the end goal, we should learn to adapt, manage, and utilize the invasive plants that are present, if at all possible. The climate is changing and semi-arid rangelands are becoming more susceptible to plant invasion (Clements and Ditommaso 2011; Clements and Jones 2021). As land managers, it is important to consider – to what degree of invasive plant infestation is 'tolerable'? In other words, when do invasive plants, such as spotted knapweed, begin to have adverse effects on the surrounding vegetation and soils?

It is also unclear which threats may be introduced into our rangelands in the future. For instance, there are species listed on the provincial Early Detection Rapid Response (EDRR), such as Medusahead (*Taeniatherum caput-medusae*) and North-Africa grass (*Ventenata dubia*) that actively being monitored for, and pose risks to invade rangelands (PoBC 2021).

Therefore, it is critical that we continue to promote adaptive and integrated land management now, and into the future.

In conclusion, perhaps it is time to rethink the standard management practice of moving cattle into mid-high elevation forested understories to graze in summer months. Instead, it may be possible to provide cattle with adequate forage and graze areas of range that have moderate to severe infestations of spotted knapweed, or other palatable invasive plants. More research should be conducted on the nutritive values of other prevalent rangeland invasive plant species found in B.C., and targeting plants other than spotted knapweed should be explored at a large scale.

REFERENCES

Bailey DW, Mosley JC, Estell RE, Cibils AF, Horney M, Hendrickson JR, Walker JW, Launchbaugh KL, Burritt EA. 2019. Synthesis paper: Targeted livestock grazing: prescription for healthy rangelands. Rangel Ecol Manag. 72(6):865–877.

Battigelli JP, McIntyre GS, Broersma K, Krzic M. 2003. Impact of cattle grazing on prostigmatid mite densities in grassland soils of southern interior British Columbia. Can J Soil Sci. 83(5):533–535.

Benzel KR, Mosley TK, Mosley JC. 2009. Defoliation timing effects on spotted knapweed seed production and viability. Rangel Ecol Manag. 62(6):550–556.

Boggs KW, Story JM. 1987. The population age structure of spotted knapweed (*Centaurea maculosa*) in Montana. Weed Sci. 35(2):194–198.

Bohnert DW, Sheley RL, Falck SJ, Nyman AA. 2014. Knapweed hay as a nutritional supplement for beef cows fed low-quality forage. Rangel Ecol Manag. 67(2):219–223.

Burritt B, Hart RA. 2014. Nutritional value and toxins in various noxious weeds. Utah State University: Logan, Utah. 15 p.

Burton CM, Burton PJ. 2003. A manual for growing and using seed from herbaceous plants native to the Northern Interior of British Columbia. Smithers, British Columbia. 168p.

Clements DR, Krannitz PG, Gillespie SM. 2007. Seed bank responses to grazing history by invasive and native plant species in a semi-desert shrub-steppe environment. Northwest Sci. 81(1):37–49.

Clements DR, Ditommaso A. 2011. Climate change and weed adaptation: Can evolution of invasive plants lead to greater range expansion than forecasted? Weed Res. 51(3):227–240. doi:10.1111/j.1365-3180.2011.00850.x.

Coffey L. 2007. Targeted grazing: A natural approach to vegetation management and landscape enhancement. Launchbaugh KL, editor. Centennial, CO: American Sheep Industry Association.

Davis ES, Fay PK, Chicoine TK, Lacey CA. 1993. Persistence of spotted knapweed (*Centaurea maculosa*) Seed in Soil. Weed Sci. 41(1):57–61.

DiTomaso JM. 2000. Invasive weeds in rangelands: Species, impacts, and management. Weed Sci. 48(2):255–265.

Dobb A, Burton SL. 2013. British Columbia rangeland seeding manual. Abbotsford: British Columbia, BC Ministry of Agriculture. 282 p.

Fraser, D. A. 2004. Factors influencing livestock behaviour and performance. Forest Practices Branch, British Columbia Ministry of Forests, Victoria, B.C. Rangeland Health Brochure 8.

Gallandt ER. 2006. How can we target the weed seedbank? Weed Sci. 54(3):588–596.

Ganguli AC, Hale MB, Launchbaugh KL. 2010. Seasonal change in nutrient composition of spotted knapweed and preference by sheep. Small Rumin Res. 89(1):47–50.

Gayton D, Miller V. 2012. Impact of biological control on two knapweed species in British Columbia. Ecosyst Manag. 13(3):1–14.

Henderson SL, Mosley TK, Mosley JC, Kott RW. 2012. Spotted knapweed utilization by sequential cattle and sheep grazing. Source Rangel Ecol Manag. 65(3):286–291.

Hobbs RJ, Hallett LM, Ehrlich PR, Mooney HA. 2011. Intervention ecology: Applying ecological science in the twenty-first century. Bioscience. 61(6):442–450.

Hook PB, Olson BE, Wraith JM. 2004. Effects of the invasive forb *Centaurea maculosa* on grassland carbon and nitrogen pools in Montana, USA. Ecosystems. 7(6):686–694.

[IAPP] Invasive Alien Plant Program. 2021. Invasive alien plant program application: A database for invasive plant data in B.C. B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development. https://maps.gov.bc.ca/ess/hm/iapp/

Kelsey RG, Locken LJ. 1987. Phytotoxic properties of cnicin, a sesquiterpene lactone from *Centaurea maculosa* (spotted knapweed). J Chem Ecol. 13(1):19–33.

Kelsey RG, Mihalovich RD. 2007. Nutrient Composition of spotted knapweed (*Centaurea maculosa*). J Range Manag. 40(3):277.

Kennett GA, Lacey JR, Butt CA, Olsonrutz KM, Haferkamp MR. 1992. Effects of defoliation, shading and competition on spotted knapweed and bluebunch wheatgrass. J Range Manag. 45(4):363.

Kimball S, Schiffman PM. 2003. Differing effects of cattle grazing on native and alien plants. Conserv Biol. 17(6):1681–1693.

Lacey, C. A., J. R. Lacey, P. K. Fay, J. M. Story, and D. L. Zamora. 1995. Controlling knapweed in Montana rangeland. Montana State University Cooperative Extension Service Circ. 311. 17 p.

Lake EC, Minteer CR. 2018. A review of the integration of classical biological control with other techniques to manage invasive weeds in natural areas and rangelands. BioControl. 63(1):71–86.

Lloyd D, Iverson K, Mackenzie K, Richardson H, Jeffries L. 2019. Laurie Guichon Memorial Grasslands Interpretive Site: A baseline inventory. Kamloops, BC. Grassland Conservation Council of British Columbia. 98 p.

Maddox DM. 1982. Biological control of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*C. maculosa*). Weed Sci. 30(1):76–82. doi:10.1017/s0043174500026217.

Marchetto KM, Wolf TM, Larkin DJ. 2021. The effectiveness of using targeted grazing for vegetation management: a meta-analysis. Restor Ecol. doi:10.1111/rec.13422.

Martin LM, MacDonald NW, Brown TE. 2014. Native plant establishment success influenced by spotted knapweed (*Centaurea stoebe*) control method. Ecol Restor. 32(3):282–294.

Maxwell JF, Drinkwater R, Clark D, Hall JW. 1992. Effect of grazing, spraying, and seeding on knapweed in British Columbia. J Range Manag. 45(2):180.

Mosley JC, Frost RA, Roeder BL, Mosley TK, Marks G. 2016. Combined herbivory by targeted sheep grazing and biological control insects to suppress spotted knapweed (*Centaurea stoebe*) . Invasive Plant Sci Manag. 9(1):22–32.

Müller-Schärer H, Schaffner U, Steinger T. 2004. Evolution in invasive plants: Implications for biological control. Trends Ecol Evol. 19(8):417–422. doi:10.1016/j.tree.2004.05.010.

Olson BE, Wallander RT, Lacey JR, Olson BE, Wallander RT, Lacey JR. 1997. Effects of Sheep Grazing on a Spotted Knapweed-Infested Idaho Fescue Community. 50(4):386–390.

Pauler CM, Isselstein J, Suter M, Berard J, Braunbeck T, Schneider MK. 2020. Choosy grazers: Influence of plant traits on forage selection by three cattle breeds. Funct Ecol. 34(5):980–992. doi:10.1111/1365-2435.13542.

Plue J, Hermy M. 2012. Consistent seed bank spatial structure across semi-natural habitats determines plot sampling. J Veg Sci. 23(3):505–516.

Province of British Columbia (PoBC). [Internet]. 2021. Early detection and rapid response (EDRR). Available from: https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/invasive-species/priority-species/priority-plants#Early%20detection%20and%20rapid%20response%20(EDRR)

Pyle LA. 2018. Influence of management and disturbance history on germinable seed bank composition and legume recruitment in Alberta's Central Parkland and Dry Mixedgrass prairie. University of Alberta.

Rinella MJ, Jacobs JS, Sheley RL, Borkowski JJ. 2001. Spotted knapweed response to season and frequency of mowing. J Range Manag. 54(1):52–56. doi:10.2307/4003527.

Rinella MJ, Bellows SE. 2016. Evidence targeted grazing benefits to invaded rangelands can increase over extended time frames. Rangel Ecol Manag. 69(3):169–172.

Rutter SM. 2010. Review: Grazing preferences in sheep and cattle: Implications for production, the environment and animal welfare. Can J Anim Sci. 90(3):285–293.

Seastedt TR, Knochel DG, Garmoe M, Shosky SA. 2007. Interactions and effects of multiple biological control insects on diffuse and spotted knapweed in the Front Range of Colorado. Biol Control. 42(3):345–354.

Sheley RL, Jacobs JS, Carpinelli MF. 1998. Distribution, biology, and management of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). Weed Technol. 12(2):353–362.

Sheley RL, Svejcar T, Maxwell B. 1996. A theoretical framework for developing successional weed management strategies on rangeland. Weed Technol. 10(4):766–773.

Solomon TB, Snyman HA, Smit GN. 2006. Soil seed bank characteristics in relation to land use systems and distance from water in a semi-arid rangeland of southern Ethiopia. South African J Bot. 72(2):263–271.

Thrift BD, Mosley JC, Brewer TK, Roeder BL, Olson BE, Kott RW. 2008. Prescribed sheep grazing to suppress spotted knapweed on foothill rangeland. Rangel Ecol Manag. 61(1):18–25.

Toledo D, Sanderson M, Spaeth K, Hendrickson J, Printz J. 2014. Extent of Kentucky bluegrass and its effect on native plant species diversity and ecosystem services in the Northern Great Plains of the United States. Invasive Plant Sci Manag. 7(4):543–552.

Watson, A. K., and A. J. Renny. 1974. The biology of Canadian weeds. *Centaurea diffusa* and *C. maculosa*. Canadian Journal of Plant Science 54: 687–701

Wilgen B van, Richardson D, Higgins S. 2001. Integrated control of invasive alien plants in terrestrial ecosystems. L Use Water Resour Res. 5:6.

Wikeem B, Wikeem S. 2004. The grasslands of British Columbia. Kamloops, BC: Grasslands Conservation Council of BC. http://doi.wiley.com/10.2307/1931227.

4. CHAPTER 4

RESEARCH SUMMARY AND MANAGEMENT IMPLICATIONS

Research Summary and Recommendations

This research assessed whether intensive grazing practices can create productive, invasive-free rangelands in the Southern Interior of British Columbia. Results from Chapter 2 demonstrated that it’s best to exercise caution if implementing management-intensive grazing (MiG) in native, semi-arid rangelands. There continues to be discrepancy as to whether MiG is beneficial to rangeland health over extensive or more conventional grazing methods (Briske et al. 2011; Teague et al. 2013). The results of the MiG treatment demonstrated promising increases in total and native grass cover, reduced bare ground, and improved diversity indices when compared to baseline conditions. However, similar results were seen within the extensive grazing enclosure. Therefore, future studies should attempt to disentangle the influence of grazing deferment or period of rest between grazing applications on vegetation and soil characteristics. A longer study duration may have painted a clearer picture of grazing effects.

There were also multiple challenges identified that may prevent the use of MiG on large land areas. First, implementing MiG on expansive crown or rural private land would be difficult due to the lack of water and fencing developments in natural range. Not only are these structures expensive, but they require a lot of maintenance. Solar panels and a battery, or an alternative an energy source is required for the electric portable fencing. Water needs to be readily accessible and available for livestock, and either needs to be transported in via truck, water pump from an adjacent water source, or built water lines. The time and labour required to manage distant pastures and adjust fencing is very consuming. Livestock also need to be trained to get comfortable with the electric fencing, and being confined in smaller enclosures. Lastly, terrain can be difficult to navigate in some areas, such as steep slopes and rocky outcrops.

That being said, MiG may be more applicable and successful when used on small-scale ranching operations, with smaller livestock herds. However, more research is needed to explore the benefits of MiG, especially if implementing multiple grazing periods throughout the year (i.e. shorter deferment periods), and grazing earlier in the spring when preferred and vulnerable bunchgrasses are actively growing.

Chapter 3 describes the first applied field study in B.C. which tested targeted cattle grazing to control spotted knapweed. Our study demonstrated that targeting spotted knapweed with cattle at the late bud – flowering stage in late July can help reduce the number of seeds produced and dispersed. However, we also observed that knapweed cover and biomass increased over a 2-year duration, possibly due to a compensatory growth response. It's recommended to supplement the targeted grazing treatment described in this study with alternative forms of weed management. This could look like:

1) Spot spraying surviving knapweed plants with a broadleaf, residual herbicide immediately after the targeted grazing treatment. This may help improve control of the ungrazed knapweed plants. This could be followed with an application of native seed in the fall, prior to snowfall.
2) An early fall application of a residual, broadleaf herbicide with an active ingredient such as 2,4-D or picloram (commercial names Grazon, Tordon 22K). This would help target plants that did not get grazed, kill rosettes that emerge in the fall, and suppress rosette and plant growth in the spring. Apply a native seed mixture in the early spring immediately after snowmelt.
3) Monitoring for existing populations of biological control insects, then release insects to initiate a population or supplement existing biocontrol populations.

Within semi-arid rangelands, it is important to practice adaptive management. Grassland ecosystems in particular can change drastically from year to year due to factors such as precipitation, periods of drought, fire, or previous year's management practices (Iverson 2004; GCC 2017; Pauler et al. 2020).

When I think of the overall scope of this research, I consider whether we should aim to 'restore' ecological communities to their original condition, or to an alternate (still functioning) state (Hobbs et al. 2011). When developing ecological restoration strategies, it’s important to consider and define goals prior to initiating the project. What features of the degraded system would you like to see improved? For instance, in an overgrazed natural grassland, is increased native plant cover and productivity a goal? Increased soil organic matter and nutrient cycling? Within a grassland ecosystem invaded with an undesirable species, what will the restored plant community look like? Invasive plant infestations tend to persist over time. What is a tolerable percent cover for the area, and what will help maintain this over time? These are all questions to consider when practicing and applying integrated rangeland management.

Further Research Opportunities

Practicing integrated land management, or applying multiple forms of weed control at once, may aid in the fight against invasive plants and promote rangeland restoration (Coffey 2007; Mosley et al. 2016; Lake and Minteer 2018). One method is biological control insects, or biocontrol. In British Columbia, there are numerous biocontrol insects that have been introduced to help control spotted knapweed invasions (Gayton and Miller 2012). Field observations suggest that there are established populations of the root feeding knapweed weevil *(Cyphocleonus achates*), the knapweed seed feeding weevil (*Larinus minutus*), and the knapweed gall fly (*Urophoa sp.*) (Gayton and Miller 2012; Seastedt and Knochel 2021). Biocontrol do not completely eradicate the target plant species; instead, following their introduction, biocontrol causes a decline in the target plant density and eventually reach an equilibrium; therefore, a ‘tolerable’ level of host plant density is achieved, which no longer causes the severe economic, social, or ecological impacts it once did (Louda et al. 2003; Barratt et al. 2017).

Moreover, the effectiveness of seeding trials following targeting spotted knapweed is still uncertain, specifically in semi-arid or dryland environments. Future research should investigate different combinations and application rates of native and agronomic seed following targeted grazing to determine if they are successful. Providing information on the existing soil seed bank is important so that it can supplemented with specialized seed applications and treatments.

Reseeding is common tool used in restoring native plant communities, however, sourcing preferred seeds can be expensive to purchase and apply at landscape scales (Burton and Burton 2003). Deciding to spread non-native or agronomic seed may also diminish the social and ecological values of native grasslands (Dobb and Burton 2013).

Therefore, for seed treatments to be successful, there are multiple considerations and requirements to be made. The timing and rate of seed application must be decided upon, and the seed mix must be suitable for the site's climate. Moreover, the seed must come into contact with mineral soil, have access to light, receive adequate moisture, and avoid predation from birds and small mammals (Dobb and Burton 2013). Attempting to seed semi-arid range is particularly difficult due to low and variable rainfall; therefore, seed establishment in dryland sites may be as low as 1% (Shakelford et al. 2021). B.C. ranching operators also may not have the capacity or resources available to make reseeding successful; moreover, seeding may not be economically feasible due to the added expenses of the seed, equipment, and labour.

Despite the challenges that come with seed applications, research shows that reseeding with native species immediately following spotted knapweed control may encourage native plant establishment and provide competition against the knapweed (Martin et al. 2014). Seed mixes that are selected specifically to compete against spotted knapweed should be investigated and developed. It would also be worthwhile to test the combined effects of targeted grazing and biocontrol on spotted knapweed density, seed bank and productivity, compared to biocontrol or grazing alone.

REFERENCES

Barratt BIP, Moran VC, Bigler F, van Lenteren JC. 2018. The status of biological control and recommendations for improving uptake for the future. BioControl. 63(1):155–167.

Briske DD, Sayre NF, Huntsinger L, Fernandez-Gimenez M, Budd B, Derner JD. 2011. Origin, persistence, and resolution of the rotational grazing debate: Integrating human dimensions into rangeland research. Rangel Ecol Manag. 64(4):325–334.

Coffey L. 2007. Targeted grazing: A natural approach to vegetation management and landscape enhancement. Launchbaugh KL, editor. Centennial, CO: American Sheep Industry Association.

Dobb A, Burton SL. 2013. British Columbia rangeland seeding manual. Abbotsford: British Columbia, Ministry of Agriculture.

Gayton D, Miller V. 2012. Impact of biological control on two knapweed species in British Columbia. Ecosyst Manag. 13(3):1–14.

Grasslands Conservation Council of British Columbia (GCC). 2017. Managing BC grasslands: an overview. Kamloops, BC. 22p.

Iverson K. 2004. Grasslands of the southern interior. Victoria, BC: Ministry of Sustainable Resource Management. 6p.

Lake EC, Minteer CR. 2018. A review of the integration of classical biological control with other techniques to manage invasive weeds in natural areas and rangelands. BioControl. 63(1):71–86.

Louda SM, Arnett AE, Rand TA, Russell FL. 2003. Invasiveness of some biological control insects and adequacy of their ecological risk assessment and regulation. Conserv Biol. 17(1):73–82.

Mosley JC, Frost RA, Roeder BL, Mosley TK, Marks G. 2016. Combined herbivory by targeted sheep grazing and biological control insects to suppress spotted knapweed (*Centaurea stoebe*). Invasive Plant Sci Manag. 9(1):22–32.

Pauler CM, Isselstein J, Suter M, Berard J, Braunbeck T, Schneider MK. 2020. Choosy grazers: Influence of plant traits on forage selection by three cattle breeds. Funct Ecol. 34(5):980–992.

Seastedt TR, Knochel DG. 2021. A 20-year evaluation of successes with biological control of spotted knapweed (*Centaurea stoebe*) in Colorado. Biol Control. 159(April):104631.

Shackelford N, Paterno GB, Winkler DE, Erickson TE, Leger EA, Svejcar LN, Breed MF, Faist AM, Harrison PA, Curran MF, et al. 2021. Drivers of seedling establishment success in dryland restoration efforts. Nat Ecol Evol. 5(9):1283–1290.

Teague R, Provenza F, Kreuter U, Steffens T, Barnes M. 2013. Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? J Environ Manage. 128:699–717.

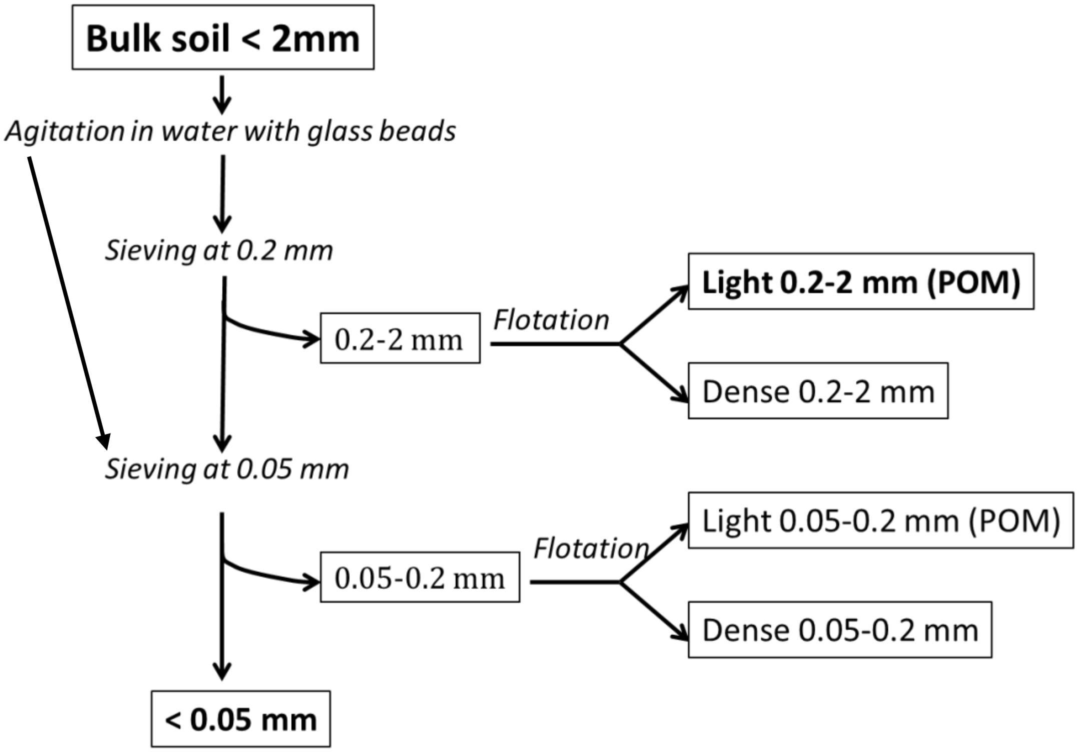
Appendix 1 – Vegetation survey plant list from Drum Lake Pasture in Merritt, B.C.

Latin Name	Common Name	Functional Group	Origin (Native/Introduced)
Achillea millefolium	Yarrow	Forbs	N
Agoseris glauca	Short-beaked agoseris	Forbs	N
Agropyron cristatum	Crested wheatgrass	Grasses	I
Alyssum alyssoides	Yellow alyssum	Forbs	I
Antennaria parviflora	Nuttall's pussytoes	Forbs	N
Arabis holboellii	Holboell's rockcress	Forbs	N
Astragalus miser	Timber milkvetch	Forbs	N
Bromus tectorum	Cheatgrass	Grasses	I
Camelina microcarpa	Littlepod false flax	Forbs	I
Centauria stoebe	Spotted knapweed	Forbs	I
Collinsia parviflora	Small-flowered blue-eyed Mary	Forbs	N
Collomia linearis	Tiny trumpet	Forbs	N
Descruainia sophia	Flixweed (Tansy mustard)	Forbs	I
Erigeron compositus	Cut leaved daisy	Forbs	N
Erigeron spp.	Purple fleabane species	Forbs	N
Eriogonum heracleoides	Parsnip-flowered buckwheat	Forbs	N
Festuca campestris	Rough fescue	Grasses	N
Festuca idahoensis	Idaho fescue	Grasses	N
Geum triflorum	Prairie smoke	Forbs	N
Hieracium gracile	Slender hawkweed	Forbs	N
Koeleria macrantha	Junegrass	Grasses	N
Lithospermum ruderale	Lemonweed	Forbs	N
Lomatium macrocarpum	Large-fruited desert-parsley	Forbs	N
Lupinus sericeus	Silky Lupine	Forbs	N
Microsteris gracilis	Slender phlox	Forbs	N
Poa pratensis	Kentucky bluegrass	Grasses	I
Poa secunda spp secunda	Sandbergs bluegrass	Grasses	N
Pseudoroegneria spicata	Bluebunch wheatgrass	Grasses	N
Rosa acicularis	Prickly rose	Shrubs	N
Taraxacum officinale	Dandelion	Forbs	I
Toxicoscordion venenosum	Meadow death camas	Forbs	N
Tragopogon dubius	Salsify	Forbs	I

Appendix 2 – The ‘Par + Den 5’ method described in the modified fractionation protocol received from the Summerland Research and Development Centre (SuRDC), one of Agriculture and Agri-food Canada’s research centres.

Sieving method for separation of fractions with different turnover rates

(based on Par+Den5 method described in Poeplau et al. 2018)



Fractionation protocol

1. Spread samples into metal pans. Pull larger root bits or living plants out of the sample. Leave in greenhouse to air-dry. If samples are really wet and/or full of lots of roots, let the sample partially air dry and then sieve (2 mm) when still fairly moist to remove roots (this should prevent contamination of the light fraction with dried out bits of freshly killed roots).

2. Otherwise, wait until samples are dry, and pass through a 2 mm sieve.

3. Store air-dried samples in plastic bags at room temperature.

4. Number and record weights of all clean beakers and pans that will contain soil or POM fractions **NOTE: use a 4 decimal scale for all measurements.**

5. Place ~50 g of soil (record wt.) in a 250 mL Erlenmyer flask, add 150mL distilled water and seven (5 mm) glass beads, swirl to mix and shake overnight (16 hours) on orbital shaker setting 4.5 (225 rpm).

6. Organize pre-weighed beakers as follows:
   a. F>50 (fraction 50-200 um, rinsed from 50 um sieve)
   b. Pan (F<50 fraction rinsed from bottom catch pan) (600mL beaker)
   c. POM>50 (floated POM panned from F>50)

7. Stack sieve catch pan, and 50 um sieve. Swirl flask and remove any debris on flask walls with stir rod and pour contents onto 50 um sieve. Rinse the flask onto the sieve. Remove glass beads with tweezers. Tap and stir soil on sieve with plastic utensils (spatulas or basting brushes) to help push liquid through.

8. Lightly rinse material on the 50 um sieve and sieve walls with spray bottle to encourage finer soil particles into the pan below. Rinse backside of sieve into the pan being careful to angle the sieve so as not to lose fractionated material on top into the pan below.

9. With scraping and minimal water, rinse the fractions from the pan (Pan F<50) and the sieve (F>50 + POM) into the appropriate labelled beakers placed inside an aluminum catch pan. Minimize spillage. Rinse soil from utensils and spillage from catch pans into appropriate fractions and then rinse all equipment once finished. At this stage, do NOT separate the POM>50 fraction from the F>50 mineral soil fraction.

   ***NOTE**: to ensure the majority of organic matter is removed from the 50um sieve, use high pressure distilled water tap to force the OM into a corner to be easily removed with spatula/more rinsing <u>after</u> thoroughly rinsing all soil/residue into beaker.

10. Label beakers with their respective sample # and fraction. Stick labels to the rim of beakers to avoid any sticker residue on the beaker. Stick labels to the rims of beakers so they can be used for the plastic vials after drying.

11. Dry all fractions at 65C until the POM in the F>50 fraction is dry before starting the following step:

Re-floatation with NaI

(only if significant organic matter is observed in the dried F>50 sample)

i) scrape/loosen all contents of the beaker

ii) based on the amount of POM present, re-float the contents of the beaker with 50mL (lower POM amount) up to 100mL of NaI solution for higher POM content.

iii) shake 5 minutes (vigorous stirring for 1 min. can be substituted for shaking)

iv) after a short settling time (~2min) the floating material is POM and the sunken material is the mineral fraction (F>50). Using a spoon, remove as much POM that floats or that can be visually identified. Add this to the POM>50 tin. (place directly onto filter paper?)

v) using a pipette, collect as much of the remaining POM as possible onto the filter paper. There is no need to minimize the amount of liquid collected in the tin as everything will be vacuum filtered.

vi) using a No. 4 Whatman paper on a Buchner funnel under vacuum, place the contents of the POM tin on the filter, then proceed to carefully pour through the filter much of the remaining NaI and floated POM from the beaker (without losing any sunken mineral fraction). Rotate the beaker as you pour to help separate the POM from the mineral soil and collect POM from beaker edges. Collect the pure NaI for re-use.

vii) rinse the POM with DH2O by flooding using a larger rinse bottle and then smaller bottle to help contain the material. Rinse until liquid is clear and any residual yellow colouring on filter paper is very faint. Clean off sides of funnel and encourage POM towards center of the filter paper using a fine spray bottle (DH2O) and spatula. Rinse POM off utensils onto paper. Shut off vacuum. Fold and remove the filter paper (now containing the rinsed POM) from the Buchner funnel and rinse (with DH2O) the contents off the filter paper into a clean, pre-weighed plastic beaker (POM>50). Rinse any residual from the funnel into beaker.

viii) Repeat these rinsing steps with the mineral fraction remaining in the beaker to remove any NaI.

ix) placed rinsed mineral fraction into a clean beaker and re-sieve through the 50um sieve and pan stack to further separate into proper fractions using the steps above. Add the contents of sieve and pan to the appropriate fractions.

x) re-dry all fractions at 65C for 48-72 hours. Cool and take final weights.

12. Grinding: use grinding mill for all samples. Alternatively, POM can be ground with mortar/pestle.

13. If sample sizes after grinding are very small, place samples directly into tin or silver foil capsules used for analysis, crimp top and replace in labelled vial.

14. Set aside unfractionated soils for further analysis:

i. DOC, by Xiying

ii. Specific surface area, by Kirsten/Andy

iii. Exchange cations/Fe/Al, by Kirsten

Equipment:

250 mL Erlenmeyer flasks (40)

Dispenser (capable of 150 mL)

Scale

Weighing scoops

5mm glass beads (300)

Tweezers

Shaker

Pan and 50um sieves

Plastic beakers, 200mL and 600mL

Small tin pans (for POM)

Scoopula and

Disposable transfer pipettes

NaI solution, d = 1.7 g/mL (Soil Sampling and Methods of Analysis (Martin R. Carter) p. 400)

Method development

Feb 12/20

In an attempt to streamline the process above we considered floating the POM right after the initial sieving (instead of first drying the F>200 with the POM in it, then floating). This meant adding NaI to a slurry of wet soil and POM. We also attempted to vacuum filter the F>200+POM fraction first to remove as much water as possible. In both cases, attempting to float the POM in NaI without drying the fraction first was difficult and much mixing of the different fractions was observed. Conclusion is that oven drying the F>200+POM is important for the efficacy of the floatation process.

Feb 20/20

Upon observing the similar 13C signatures of the coarse (F>200) and fine (F>50) sand fractions it is likely not useful to have these as separate fractions. For this reason, the 200um sieve could be eliminated. The advantages are:

i) All sand combined into one fraction
ii) Reduced sample numbers
iii) Flotation with NaI will now help in capture POM>50, not just POM>200

Appendix 3 – Summarized vegetation survey data for the targeted and control treatment enclosures at Drum Lake Pasture.

				Mean % Cover (+/- 1 SE)	
Common name	**Scientific name**	**Functional group**	**Status**	**Targeted**	**Control**
Dandelion	*Taraxacum officinale*	Forbs	Introduced	.9 ± .53	1.1 ± .41
Meadow death camas	*Toxicoscordion venenosum*	Forbs	Native	0	.7 ± .52
Flixweed (Tansy mustard)	*Descruainia sophia*	Forbs	Introduced	1.6 ± .73	.2 ± .20
Holboell's rockcress	*Arabis holboellii*	Forbs	Native	.6 ± .31	.5 ± .34
Lemonweed	*Lithospermum ruderale*	Forbs	Native	.2 ± .20	0
Nuttall's pussytoes	*Antennaria parviflora*	Forbs	Native	0	4.6 ± 3.0
Parsnip-flowered buckwheat	*Eriogonum heracleoides*	Forbs	Native	7.3 ± 4.2	9.0 ± 3.7
Purple fleabane species	*Erigeron spp.*	Forbs	Native	0	.7 ± .52
Salsify	*Tragopogon dubius*	Forbs	Introduced	.5 ± .34	1.6 ± .48
Small-flowered blue-eyed Mary	*Collinsia parviflora*	Forbs	Native	0	.1 ± .10
Silky Lupine	*Lupinus sericeus*	Forbs	Native	8.4 ± 2.67	19.5 ± 6.52
Slender phlox	*Microsteris gracilis*	Forbs	Native	.3 ± .15	.1 ± .10
Spotted knapweed	*Centauria stoebe*	Forbs	Introduced	16.5 ± 2.95	16.1 ± 5.85
Timber milkvetch	*Astragalus miser*	Forbs	Native	4.0 ± 1.0	.3 ± .30
Tiny trumpet	*Collomia linearis*	Forbs	Native	.1 ± .10	.5 ± .31
Yarrow	*Achillea millefolium*	Forbs	Native	16.1 ± 2.58	18.2 ± 3.62
Yellow alyssum	*Alyssum alyssoides*	Forbs	Introduced	.7 ± .42	.6 ± .43
Bluebunch wheatgrass	*Pseudoroegneria spicata*	Grasses	Native	8.0 ± 1.61	0
Kentucky bluegrass	*Poa pratensis*	Grasses	Introduced	2.2 ± 1.13	3.0 ± 1.34
Junegrass	*Koeleria macrantha*	Grasses	Native	7.7 ± 2.14	3.9 ± .77
Sandbergs bluegrass	*Poa secunda spp secunda*	Grasses	Native	4.3 ± .84	4.2 ± 1.13
Cheatgrass	*Bromus tectorum*	Grasses	Introduced	.1 ± .10	0
Idaho fescue	*Festuca idahoensis*	Grasses	Native	1.7 ± 1.16	11.9 ± 2.35
Rough fescue	*Festuca campestris*	Grasses	Native	0	1.8 ± 1.5
Ground Parameters					
Bare Ground				6.9 ± 1.66	3.9 ± 1.35
Rock				4.5 ± .85	2.6 ± 1.43
Litter				13.5 ± 1.2	21 ± 4.65
Crust				3.3 ± 1.34	3.5 ± 1.0
Dung				1.2 ± .1.0	.1 ± .10