EXAMINING THE EFFECTS OF MOWING, IRRIGATION, AND FERTIILZATION ON PLANT PRODUCTIVITY AND SOIL CARBON LEVELS OF PERENNIAL CROPPING SYSTEMS

by

SARAH JEAN BAYLIFF

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Thesis Examining Committee:

Lauchlan Fraser (PhD), Professor and Thesis Supervisor, Department of Natural Resource Sciences, Thompson Rivers University
Wendy Gardner (PhD), Associate Professor and Committee Member, Department of Natural Resource Sciences, Thompson Rivers University, Thompson Rivers University
David Hill (PhD), Professor and Committee Member, Department of Geography and Environmental Studies, Thompson Rivers University
External Examiner

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Thompson Rivers University

Abstract

With the growing concern of climate change, there is increasing pressure on the agricultural industry to alter management techniques to become more environmentally sustainable while still maintaining production of quality crop yields. Three commonly used management techniques, mowing, irrigation, and fertilization, were tested on plant and soil characteristics to determine the best practices for managing land to be both productive and sustainable. Two enclosures were established on a perennial cropping system in the interior of British Columbia. One enclosure was constructed on active cropland that was irrigated and fertilized. A second enclosure was located on abandoned cropland which had not been irrigated or fertilized for over twenty years. Within the active enclosure, different mowing heights were implemented, ranging from zero to thirty centimetres at five-centimetre intervals. Treatments were applied twice throughout both 2020 and 2021 growing seasons. Measures of plant community dynamics, plant productivity, forage quality, and soil properties were taken from within both enclosures throughout the duration of the study. Results showed that each of these three management techniques effected plant productivity and soil carbon. Mowing height altered forage species composition, plant productivity, forage quality, and soil properties. Use of a 10 cm cutting height produced highest levels of plant productivity and soil carbon. The abandonment of irrigation and fertilization was shown to cause unfavourable plant community changes along with decreases in plant productivity, forage quality, and soil carbon. These results provide insight on the use of these three management techniques within perennial cropping systems and their effects on levels of plant productivity and soil carbon. The implications of this study allow producers throughout interior British Columbia to make informed decisions on how to manage their land for optimum productivity and environmental sustainability.

Dedication

I would like to dedicate this thesis to my father, Michael Bayliff. His work ethic and breadth of knowledge is an inspiration to me. Without him, this project would not have been possible. Thank you for providing me the space on the ranch to conduct this study, taking time to help with the mowing, sharing your lunch with research assistants, and providing guidance and support throughout the duration of my project. Cheers, Dad.

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Chapter 1 INTRODUCTION

For centuries, agriculture has been a necessity to feed the human population, allowing for the modern expansion of civilization and economic growth (Federico 2009). Today, agriculture continues to support humankind by providing sustenance, creating employment opportunities, and contributing revenue to the global economy. While a necessity for human survival, agriculture also has the reputation of causing environmental damage through such activities as land conversion and contribution to pollution. In order for agriculture to remain relevant in a modern, environmentally conscious world, the industry must find ways to reduce its environmental impacts. Focussing on the impacts of agriculture, a land-use which occupies 49% of the global ice-free land surface (Ledo et al. 2020) has incredible potential to help combat anthropogenic contributions to the changing climate, while continuing to produce quality products that nourish the global population.

The Importance of Agriculture in British Columbia

Agriculture is an important contributor to Canada's economy, generating $139.3 billion of gross domestic product and employing approximately 2.1 million people in 2020 (Overview of Canada's Agriculture and Agri-food Sector 2021). Across British Columbia (B.C.), over 4.6 million hectares of land are designated as agricultural land reserves (ALR) (Ference & Company Consulting Ltd 2016). ALR are provincial zones in which the priority land use is agriculture. This jurisdiction helps preserve land for agricultural use, restricting other land uses. These areas span throughout the province (Figure 1.1), and even though they occupy under 5% of BC's land mass, they annually contribute $3.2 billion to the country's economy (Hawkins and Townsend 2019) and are BC's "best food-producing land" (Townsend 2020).

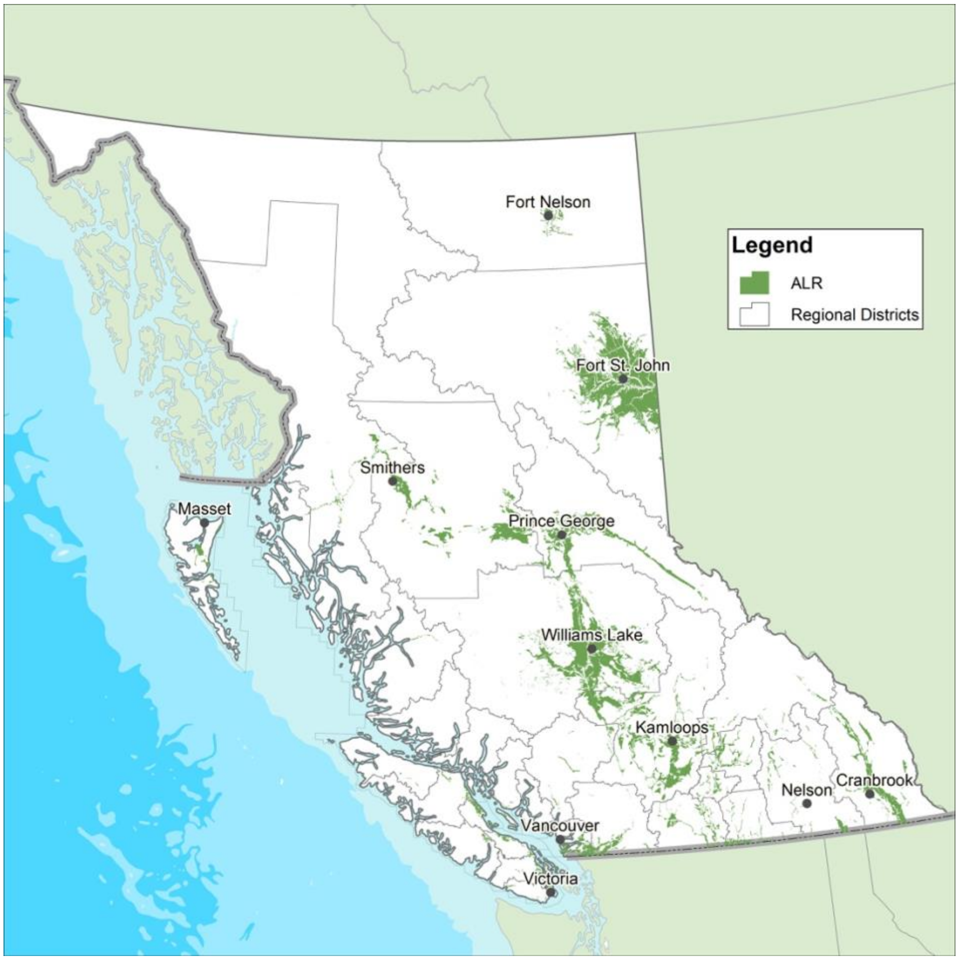

Figure 1.1:Map of B.C. showing distribution of Agricultural Land Reserves (Provincial Agricultural Land Commission 2014).

B.C.'s geography is very diverse, containing many climatic regions, and thus can support a wide variety of agricultural sectors, ranging from fruit and vegetable production to meat and poultry operations. Each sector has its own place in the province's supply chain and economy.

Environmental Concerns Regarding Agriculture

While agriculture is important for the livelihoods of British Columbia's citizens and economy, there remains concern regarding the effects of agricultural activities on the environment. It is well documented the negative impacts agriculture can have on natural ecosystems (Steinfeld et al. 2006). The industry has been strongly critiqued for destruction of habitat through land conversion, pollution of groundwater through leaching of fertilizers and pesticides (Arroita et al. 2013; Adejumobi et al. 2016), and contribution to greenhouse gas (GHG) emissions through the release of carbon dioxide, methane, and nitrous oxide (Greenhouse Gases and Agriculture 2020). Amidst these detriments, the agricultural industry is very reliant upon environmental conditions for successful production and the changing climate is expected to affect agricultural production both environmentally and economically.

Environmentally, climatic regimes are expected to shift to prolonged periods of drought, ultimately affecting forage and crop production (Cox et al. 2015). Economically, producers will face higher costs for necessary purchases, including fertilizers, seed, and feed, as production of these goods is also affected by the shifting climate (Harrower et al. 2012). As potential for production decreases and price of operation increases, agriculturalists are facing financial hardships while trying to keep their businesses viable. However, the need for agricultural products is only expected to grow as the world's human population and food demand continues to increase (Howden et al. 2007). Agricultural producers are now facing contradictory situations. At a time when crop production is low, and costs of operation are high, higher levels of production are required.

With the growing human population, impeding threats of climate change, and rising environmental concerns, there is increasing pressure on the agricultural industry to become more environmentally sustainable while continuing to maintain production. Not only will this industry have to change its management techniques to reduce environmental impacts, but practices must also become better adapted to the changing climates, both environmental and economic (Howden et al. 2007). Land must be managed to maintain productivity and promote sustainability in the midst of the shifting climate to ensure continuous revenue, allowing agriculturalists to continue contributing to the province's economy (Harrower et al. 2012). This goal may be achieved by improving current agricultural management practices to provide both environmental and economic benefits, while producing crops that are resilient to climate change and continue to feed the country's population and economy (Climate Action for Agriculture 2020).

Forage Production in British Columbia

In B.C., forage production is a major use of agricultural land, with 75% of the province's farmland being used to produce forage (Ference & Company Consulting Ltd 2016). This large span of land plays a role in supporting the economies of rural communities, climate change mitigation and adaptation, and sustains the province's beef, sheep, and dairy industries (Ference & Company Consulting Ltd 2016). Forage crops across B.C. include a wide range of both annual and perennial species (Forage 2020). Compared to annual cropping systems, utilizing a perennial cropping system can be advantageous for the sustainability of agricultural land. A perennial cropping system eliminates the need for annual tilling and seeding and allows for the land to store biomass in unharvested shoot and root material, reducing GHG emissions and increasing levels of carbon sequestration (Ledo et al. 2020). The great area of the province covered by perennial forage crops, and their potential to help combat GHG emissions, makes proper management of these landscapes crucial for economic stability, environmental sustainability, and the continuation of the livestock industries of B.C.

Agricultural Management Practices

Agricultural management practices refer to methods used in agriculture in order to produce better agricultural products (Agrotechnology 2020). Management techniques could range from fertilizing a field for increased crop production or inoculating a cattle herd for protection from a virus. Typically, the common goal of these techniques is to increase production. Using agricultural management techniques to increase production of perennial forage crops not only provides more feed for livestock, but also gives producers the opportunity to combat their GHG emissions by sequestering atmospheric carbon within the soil and in plant material (Conant et al. 2001). The amount of soil organic matter and vegetation present on agricultural land is positively correlated with the amount of carbon sequestration occurring (Greenhouse Gases and Agriculture 2020). If producers change management practices to increase production, they are also increasing the amount of carbon dioxide being captured from the atmosphere by their crops, helping to potentially turn their agricultural land into a carbon sink (Conant et al. 2001).

Several agricultural management practices that are commonly utilized in agricultural operations and can be used to increase yield and rates of carbon sequestration include mowing (Turner et al. 1993; Maron and Jefferies 2001; Zhao et al. 2008; Bernhardt-Römermann et al. 2011; Ziter and Macdougall 2013; Wang et al. 2014; Wan et al. 2016; Yang et al. 2020), irrigation (Conant et al. 2001; Arroita et al. 2013; Adejumobi et al. 2016; Müller et al. 2016; Alavaisha et al. 2019; Li et al. 2019), and fertilization (Conant et al. 2001; Bernhardt-Römermann et al. 2011; Ziter and Macdougall 2013; Müller et al. 2016).

Mowing

In agricultural practices, mowing is typically used to harvest forage crops so they can be stored as winter feed for livestock. For areas with harsh winter climates, such as much of interior and northern B.C., this practice is a necessity for most livestock producers in order to feed their herds (Jungnitsch et al. 2008). While mowing is essential for many operations, it also has potential as a management technique and can be used to alter biomass production and species composition (Wan et al. 2016). Mowing has the ability to affect plant production through the mechanism of compensatory growth, in which plants compensate for defoliation through the production of new roots and shoots (McNaughton 1983; Huhta et al. 2013). Mowing has been shown to stimulate this mechanism, and thus can be used to increase plant production (Turner et al. 1993; Zhao et al. 2008; Ziter and Macdougall 2013; Wang et al. 2014; Wan et al. 2016; Yang et al. 2020). This increase in productivity has potential to increase soil organic matter (Conant et al. 2001). While variables such as nutrient availability and individual plant species can determine levels of compensatory growth, the factors of mowing time, mowing height, and mowing frequency can also have an impact on how crops respond to the process of defoliation (Wan et al. 2016).

The ability of mowing to alter levels of plant productivity and soil carbon and its frequent use in forage operations across the province make it a valuable tool in managing agricultural land. Better understanding the management implications of this technique will allow mowing to be best applied for productivity and sustainability.

Irrigation

Irrigation is another commonly used technique in agricultural operations. In dryer climates, irrigation is essential to provide sufficient moisture for crop growth. Due to the short, dry growing season of the Cariboo-Chilcotin region of B.C., a lot of ALR land is utilized as irrigated fields, with 14% of all crop area in this region being irrigated (Ference & Company Consulting Ltd 2016). Ranchers rely on irrigation to produce enough forage throughout the short growing season to feed their livestock throughout the long winters. Like mowing, irrigation also has potential to be used as a management technique. Studies have shown that irrigation is capable of increasing carbon sequestration through increased plant productivity (Conant et al. 2001; Arroita et al. 2013) and by facilitating the faster breakdown of organic material (Arroita et al. 2013). Irrigation can also add other benefits to the soil, such as improving soil fertility (Alavaisha et al. 2019) and microbial activity (Arroita et al. 2013), both of which are important for plant production and carbon storage. However, if not managed properly, irrigation can also have negative impacts on the landscape including increased run-off, leaching of pesticides and fertilizers, and pollution of groundwater (Arroita et al. 2013; Adejumobi et al. 2016). The effects of irrigation on agricultural hay fields are still lacking research. To better understand the effects of irrigation on both crop yield and the chemical and physical properties of the soil, further research needs to be performed so proper management techniques can be implemented.

Fertilization

Fertilization, either organic or inorganic, is frequently used in the agricultural industry to enhance crop yields. This process typically includes adding various nutrients to the soil to increase plant production (Han et al. 2014). Similar to other management techniques that increase plant productivity, fertilization also can increase the amount of soil carbon storage occurring on a landscape (Conant et al. 2001; Ziter and Macdougall 2013). Fertilization also raises environmental concern as it has the potential for nitrogen leaching and contribution to GHG emissions through the release of nitrous oxide (Qian et al. 2003). Fertilization is commonly an annual occurrence and can cost ranchers over $20,000/square kilometre to maintain the productivity of their land (Appendix A, Figure A.1). If used and applied properly, fertilization can maximize benefits while reducing environmental impacts. Studying the effects of fertilization will allow for a better understand of its interaction with plant and soil communities and help provide information to weigh the costs and benefits of fertilizer application.

Thesis Research Objectives

This study examined the use of different agricultural management techniques – mowing, irrigation, and fertilization – and their ability to improve the productivity and sustainability of perennial forage crops on a hay field near Alexis Creek, B.C. To achieve this, a two-year field study was conducted with the objectives of; 1) investigating the effects of mowing height on forage production and soil characteristics; and 2) examining plant and soil response to abandonment of irrigation and fertilization. The results of this thesis contributed information that allows agricultural producers across the province to make well-informed decisions on how to manage their land to become more productive and environmentally sustainable.

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Chapter 2 - THE EFFECTS OF MOWING HEIGHT ON PLANT PRODUCTIVITY AND SOIL CHARACTERISTICS OF PERENNIAL CROPPING SYSTEMS

INTRODUCTION

Forage crops occupy 75% of British Columbia's (B.C.) agricultural land (Ference & Company Consulting Ltd 2016). These crops are used to feed various forms of livestock throughout the year, either through grazing in the summer months or through production of hay and silage to be used for winter feed. The production of winter feed is important in B.C. to provide sustenance to animals throughout the winter when foraging and grazing is unavailable due to lack of plant growth and increased snow cover (Jungnitsch et al. 2008). Therefore, successful production of forage crops is a necessity for the continuation of the livestock industry within B.C. While general management of forage crops across the province may vary between practices, mowing is a common technique amongst most operations.

Mowing is the practice of harvesting aboveground biomass (Yang et al. 2020), typically for the production of winter feed. Along with producing agricultural products, mowing also has potential to alter plant productivity, plant diversity, and eventually, soil characteristics. These variables can all be affected through differing mowing intensities, which incorporates mowing height, frequency, and timing (Yang et al. 2020, Wan et al. 2016, Han et al. 2014, Wang et al. 2014, Lü et el. 2012, Zhao et al. 2008, Maron and Jefferies 2001, Turner et al. 1993).

Plant productivity is thought to be stimulated by mowing through the mechanism of compensatory growth (McNaughton 1983, Huhta et al. 2003). Compensatory growth is defined as a growth response that allows for a plant to counteract the tissue lost to defoliation through the production of new plant material (McNaughton 1983). Defoliation represents a massive decrease in a plant's ability to photosynthesize as a large amount of leaf area is removed. The goal of compensatory growth is to return the plant's function to pre-defoliation conditions, thus nutrient allocation is shifted to produce new plant material to increase photosynthetic capacity (McNaughton 1983; Briske and Richards 1995). This response is thought to be due to high levels of cytokinins, which are plant hormones within root systems that promote cell division (McNaughton 1983). Defoliation increases the root to shoot ratio, and thus also increases concentrations of cytokinins within a plant. These hormones are allocated to remaining aboveground plant tissue where they stimulate cell division and allow for plant regrowth following defoliation (McNaughton 1983; Briske and Richards 1995). Production of a compensatory growth response is dependent upon many factors, including the amount of photosynthetic material remaining after defoliation, levels of carbohydrate reserves within rooting systems, phenological stage at time of defoliation, and resource availability following defoliation (McNaughton 1983; Briske and Richards 1995). Because of the dependence of compensatory growth on all these factors, levels of this mechanism vary with defoliation intensity and timing, species composition, and environmental conditions.

Increased compensatory growth is favourable for both producers and the environment; increased shoot production yields more aboveground biomass for forage, while increased root production adds more carbon to the soil (Ferraro and Oesterheld 2002). Through this mechanism, increased plant productivity has potential to increase the carbon stocks of agricultural land. Therefore, the ability of mowing to influence carbon sequestration makes it a possible way to help mitigate climate change and environmental impacts caused by agriculture (Ferraro and Oesterheld 2002). However, while a commonly utilized practice, the exact response of plants to mowing is still not well understood (Yang et al. 2020).

Previous studies have investigated mowing intensity as a determining factor in how plants respond to this practice. A high mowing intensity often refers to a low cutting height or high frequency of cuts. On the other end of the spectrum, low mowing intensity involves a higher cutting height or lower frequency of cuts. Using a high mowing intensity has been shown to decrease levels of compensatory growth, and therefore plant productivity (Yang et al. 2020, Wan et al. 2016, Zhao et al. 2008). Low cutting heights remove all aboveground biomass, which can increase bare ground exposure and reduce the amount of nutrient return to the soil (Yang et al. 2020, Han et al. 2014), resulting in unfavourable conditions for both plant and soil communities. High intensity mowing can also cause increased levels of defoliation that some plants may not be able to recover from, threatening species richness and biodiversity (Tälle et al. 2014). Low intensity mowing has also been shown to cause changes in the plant community. Zhao et al. (2008) found that using a higher cutting height caused less damage to plants, leaving adequate resources for them to produce compensatory growth. Through defoliation of dominant species, mowing can reduce levels of competition, resulting in growth of less competitive plant species and increases in biodiversity (Grime 1977), with maximum diversity occurring at levels of moderate defoliation (Grime 1973). Using a higher cutting height does not reduce competition compared to lower cutting heights, and thus does not favour increases in biodiversity (Wan et al. 2016). Furthermore, leaving a high stubble height may eventually lead to decreased long-term regrowth through build-up of plant litter, and thus decreased biomass production (Wan et al. 2016). These studies showed that mowing intensities that are either too high or too low can both have negative impacts on the plant communities of agricultural land, and that there is a relationship between level of defoliation and resulting changes in plant productivity and community diversity (Grime 1973; Grime 1977; McNaughton 1983).

While mowing has been shown to affect plant productivity and community dynamics, there are knowledge gaps regarding how agricultural land responds to mowing (Yang et al. 2020). A serious lack of understanding exists when considering the response of the soil community to mowing. Many studies choose to focus on the aboveground responses of mowing, as plants usually respond quickly to disturbance. However, more focus is needed on the long-term response of soil to mowing to determine the ideal mowing practice (Yang et al. 2020). Levels of soil carbon and nutrients both correlate with levels of carbon sequestration and plant productivity (Conant et al. 2001). Understanding how different mowing intensities affect these soil qualities will allow producers to use this practice to increase both the productivity and sustainability of their crop land.

Regardless of mowing intensity, how a crop will respond to mowing is also greatly dependent on climate, previous management history, and crop type. Climate, including mean annual temperature and precipitation, can impact plant response to mowing. For example, drought-prone areas may be less resilient to mowing than areas where moisture is not a limiting factor (Zhao et al. 2008). Management history also plays a role when deciding upon mowing regimes. Areas that have been historically fertilized will show higher productivity and thus will be able to withstand higher mowing intensities (Bernhardt- Römermann et al. 2011). Lastly, plant response to mowing is crop specific. Some species show great differences in their ability to produce compensatory growth.

Responses could range anywhere from immediate death to increased production (Huhta et al. 2003).

When considering forage crops throughout B.C., there is limited information on response to mowing. Many previous studies focus on species that are not native to Canada and reside in continents whose climates are quite dissimilar from B.C. Because forage crops are repeatedly mowed for harvest, understanding the response of these crops to mowing remains an important management implication. Using proper mowing practices to achieve optimum plant productivity allow producers a way to increase their yields while also mitigating emissions through inputs to soil carbon and carbon sequestration (Conant et al. 2001). Understanding how forage crops of B.C. respond to mowing will provide information on how to manage agricultural land for increased productivity and environmental sustainability.

This chapter summarizes the results of a field experiment that tested the effects of mowing on the plant and soil characteristics of a perennial cropping system in the interior of B.C. This experiment answered the questions of how do varying mowing heights affect 1) plant community diversity and forage species composition, 2) aboveground and belowground plant productivity through the mechanism of compensatory growth, 3) forage quality, and 4) levels of soil carbon and nutrients of a perennial cropping system? With respect to the second question, it was hypothesized that maximal compensatory growth would be seen within the moderate mowing treatments (>10 cm and <20 cm), as these heights stimulate the compensatory growth mechanism explained above, while preserving already present photosynthetic material. This hypothesis is supported by previous literature which examined how compensatory growth varies with cutting height (Yang et al. 2020; Wan et al. 2016; Wang et al. 2014; Zhao et al. 2008; Huhta et al. 2003; Turner et al. 1993).

MATERIALS & METHODS

Field Study Design

Study site

In April of 2020, a research site was established on Newton Ranch, located approximately 136 kilometres west of Williams Lake, British Columbia. Newton Ranch is a 3500-acre beef cattle operation, with 800 acres of land being used as irrigated cropland. The study site is located within an IDFxm biogeoclimatic zone, which contains forested regions at higher elevations, and grasslands at lower elevations in valley bottoms (Steen and Coupe 2002). This property is located just west of the Chilko and Chilcotin Rivers' junction, and native vegetation ranges from stands of interior douglas fir (*Pseudotsuga menziesii*) to fields of bluebunch wheatgrass (*Pseudoroegneria spicata*). This area receives approximately 493 mm of annual precipitation, has an average annual temperature of 4.0° C (Moore et al. 2010), and an elevation of 777 m.

The research site was constructed on one of the fields used for crop production (lat. 52.08252º N, long. 123.52085º W). Historically, this field has been excluded from cattle grazing and is biannually mowed to harvest plant material. In 2009, the field was tilled and seeded with a perennial forage blend with an application rate of 21.3 kg/ha. Refer to Table 2.1 for a list of seeded species and their relative composition of the seed mix. Irrigation was delivered to the study area by a centre pivot sprinkler system which typically runs annually from May to September. The irrigated cropland was fertilized in May, similar to previous years, with an inorganic fertilizer composed of 50% nitrogen, 20% phosphorus, 20% potash, and 10% sulphur, with an application rate of 214.6 kg/ha (see Appendix A, Figure A.1).

Table 2.1:Species composition of forage blend seeded on field site in 2009.

Seeded species	**Composition (%)**
Climax timothy (*Phleum pratense*)	25%
Altaswede Red Clover (*Trifolium pratense*)	25%
Leader Alfalfa (*Medicago sativa*)	50%

Experimental design

In April of 2020, a study enclosure was mapped out on irrigated, perennial cropland at the research site. The enclosure measured approximately 10 m x 100 m and was divided into six blocks, representing six replicates. Each block was organized into 2 m x 2 m plots, including 1 m buffer strips between plots (see Figure 2.1). The four corners of each plot were marked with irrigation flags.

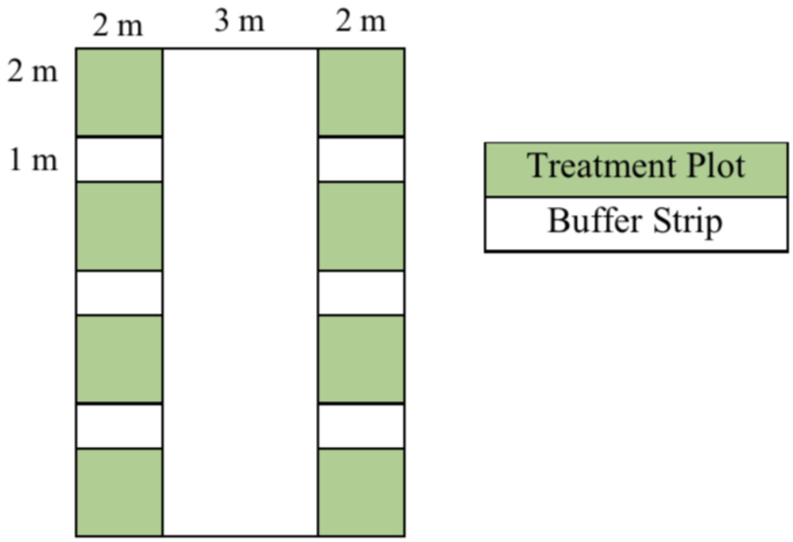

Figure 2.1:Experimental plot layout within study block.

Each 2 m x 2 m plot was assigned an experimental treatment. Each study block consisted of one of each treatment listed in Table 2.2. Treatments were randomly assigned to plots to create a randomized block design.

Table 2.2: Experimental treatments and corresponding codes for field study.

Code	**Treatment Type**
M0	Mowed at 0 cm
M5	Mowed at 5 cm
M10	Mowed at 10 cm
M15	Mowed at 15 cm
M20	Mowed at 20 cm
M25	Mowed at 25 cm
M30	Mowed at 30 cm
Control	Not mowed

Following fertilizer application, the enclosure was fenced with 2 m high electric fencing to exclude grazing from ungulates throughout the duration of the study. See Figure 2.2 for completed experimental set-up. For a detailed map of field site, see Appendix D.

Figure 2.2: Completed experimental set-up showing plot design on irrigated cropland.

Site monitoring

Biweekly site monitoring occurred in 2020 from May to October and in 2021 from April to August. This involved taking soil moisture readings using a FieldScout TDR 300 soil moisture probe within each plot throughout the study enclosure. Soil moisture readings were produced through time-domain reflectometry (TDR) and were given as volumetric water content (VWC) (%), which is a ratio of water volume within a given volume of soil to total soil volume (Spectrum Technologies 2009). TDR is a quick and accurate method of determining VWC which involves the insertion of stainless-steel rods below the soil surface. The probe generates and senses the return of an energy signal between the two rods. The speed of this signal is dependent on the water content of the soil, with more-moist soils showing higher speeds. This relationship allows the timing of the electrical signal to be converted to VWC (Spectrum Technologies 2009). Site monitoring also included biweekly mowing of the buffer strips between plots to ensure plot perimeters were kept visible.

This mowing was carried out using a Husqvarna 160cc 3-in-1 Push Lawn Mower. During site monitoring, photos were taken of each individual plot to record growth stages of vegetation.

Weather monitoring

In May 2020, a HOBO weather station equipped with a rain gauge, air temperature sensor, wind speed and direction sensor, and USB Micro Station was installed on the perimeter of the research site, away from the reach of the irrigation system. From May to October 2020 and April to August 2021, precipitation and air temperature data were collected. Data were exported from the USB Micro Station biweekly during the recording intervals. From this data, average values of precipitation and temperature were calculated for each study year.

Irrigation monitoring

From May to September throughout both study years, irrigation was applied to the study enclosure by a centre pivot sprinkler system. To estimate levels of irrigation, a logbook was kept recording the duration and speed the sprinkler system was running. Using this data, along with the estimated output of the pivot (see Appendix B, Figure B.1), an approximate amount of irrigation applied was able to be calculated for each study year. See Appendix B for calculations of average irrigation applied throughout growing seasons.

Experimental treatments

For this study, mowing intensity was defined by the function of mowing height. Experimental treatments (shown in Table 2.2) included mowing heights of 0 cm, 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, and a control treatment. Mowing treatments from here forward will be referred to using the codes listed in Table 2.2. Study plots that were assigned the control treatment were not mowed for the duration of the study. Mowing treatments were applied to plots three times throughout the study, with a final harvest occurring at the study's end date. See Table 2.3 for specific harvest dates.

Table 2.3: Type and date of harvest performed throughout study duration.

Harvest Type	**Date of Harvest**
Treatment Application	June 24th, 2020
Treatment Application	August 26th, 2020
Treatment Application	June 23rd, 2021
Final Harvest	August 24th, 2021

Mowing treatments were applied using a New Holland 411 discbine mower pulled behind 1974 Case 870 tractor. A large bag was attached to the deflector panels of the mower to capture all cut biomass (see Figure 2.3). For each mowing treatment, the deck of the mower was lowered to the appropriate height. Heights were manually measured using rulers which had been cut to match the treatment heights. M0 plots were then mowed on the lowest setting of a Husqvarna 160cc 3-in-1 Push Lawn Mower to ensure the vegetation was taken down to the lowest height possible (approximately 2 cm). Cut biomass was emptied from the bag in an area outside of the study enclosure. Any cut biomass that had not been collected was manually raked and removed from the study enclosure. After mowing, vegetation height within each plot was measured to ensure it had been cut at the proper height. If there were any discrepancies, adjustments were made manually using garden shears.

Figure 2.3: Tractor and mower, fit with collection bag, implementing the mowing treatments in the study enclosure in June 2021.

Data Collection and Analysis

Aboveground vegetation assessment

Before each mowing event, height measurements, vegetation surveys, and biomass samples were collected from each study plot. Height measurements were collected from nine points within each plot (see Figure 2.4A), recording plant species along with the distance from the base to tallest point of the plant. The tallest plant's height and species was also recorded within each plot. Vegetation surveys were performed using a 0.25 m^2 quadrat frame, recording species present and estimating absolute percent cover. Surveys were performed in each plot at two randomly determined locations out of nine possible survey locations (see Figure 2.4B). From these surveys, Shannon-Weiner diversity (see Equation 1) and species richness were determined. Species richness gives the simplest measure of diversity, while the Shannon-Weiner index factors in the evenness of species' distribution. Using both diversity metrics provides more insight into plant community dynamics than considering one measure of diversity alone (Morris et al. 2014).

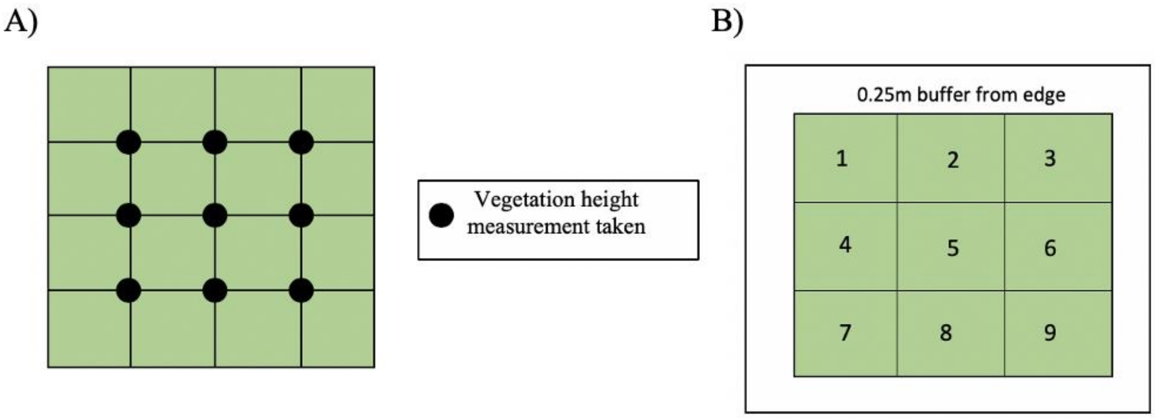

Figure 2.4: Experimental plot showing where A) vegetation height measurements, and B) vegetation surveys were performed.

Equation 1:

$$Shannon - Weiner\ Index\ (H) = -\sum_{i=1}^{s} pi\ ln\ pi$$

Aboveground biomass samples were taken from the same 0.25 m^2 quadrat areas where vegetation surveys had been collected. Biomass samples were collected at the corresponding treatment height for each study plot. At June and August 2020 and June 2021 sampling events, biomass samples were not taken within control plots. In August 2021, after biomass samples were collected at treatment height, all remaining biomass was collected, including within control plots, at a height of 0 cm to allow for a final comparison of cumulative aboveground biomass production between treatments. Once collected, biomass samples were placed in paper bags and dried for 48 hours at 65 °C in a Yamato DKN812 drying oven after which they were weighed using a Fisher Scientific accuSeries 4102 top-loading scale to determine total dry sample weight. Cumulative biomass for each mowing treatment was determined by adding together the biomass values from all four sampling events listed in Table 2.3.

Plant regrowth after mowing was estimated using height measurement data. To estimate the amount of regrowth two-months after mowing, the treatment height was subtracted from the

August height measurements across mowing treatments. The change in plant height two months after being cut to treatment height was used as a predictor of regrowth after application of mowing treatments. For control plots, two-month regrowth response was estimated by subtracting the June height measurements from August height measurements. Any estimations that were calculated to be negative values were changed to zero, as ‘negative regrowth’ is not possible.

Belowground productivity

In September 2020 and August 2021, root biomass samples were taken to assess belowground biomass production. Two 10 cm^3 volumes of soil from the top 10 cm of soil were taken from each study plot. Sampling occurred within the inner 1 m^2 of the plot, with samples being taken in two of the corners in 2020 and the other two corners in 2021 (see Figure 2.5). Dimensions of the sample were measured with a ruler and trimmed to the appropriate size using a soil knife (see Fig 2.6A). Whole samples were then dried for 48 hours at 65 °C in a Yamato DKN812 drying oven. Once dried, samples were passed through a 2 mm sieve to remove the soil from the roots. The remaining roots were then washed using a spray nozzle to remove access dirt (see Fig. 2.6B). Washed roots were then dried for another 48 hours at 65 °C and then weighed to determine their final dry sample weight (see Fig.2.6C)

Figure 2.5: Location of root biomass sampling within study plot.

Figure 2.6: Method of root biomass collection: A) Field sample collection; B) Washing roots to remove dirt; C) Weighing washed and dried roots for final sample weight.

Forage quality analysis

Subsamples of dried biomass samples for M0 and M30 treatments from June 2020, August 2020, and June 2021 were sent to Fraser Analytical Services in Abbotsford, B.C. where near-infrared (NIR) analysis was completed to determine forage quality. Results on forage analyses were given in values of percent of dry matter (% DM). The variables chosen to represent forage quality in this study were crude protein, soluble protein, acid detergent fibre (ADF), lignin, and total digestible nutrients (TDN). These five metrics were chosen as they are all good indicators of and are frequently used to describe forage quality (Ball et al. 2001; Schroeder 2006), they were also all included in Fraser Analytical's basic NIR package.

Final soil sampling

In August of 2021, following the final harvest, soil samples were taken. Soil samples were taken from the 2021 root biomass sample locations at depths of 0-15 cm and 15-30 cm. Soil from the two sampling locations were combined according to depth, resulting in one sample per depth for each study plot. Soil samples were analyzed for levels of soil organic matter, total carbon, and total nitrogen.

Soil organic matter

To determine levels of soil organic matter, fresh soil was used. Soil was first dried for sixteen hours at 105 °C in a Yamato DKN812 drying oven. The dried soil was then weighed to determine dry soil weight. Samples were then burned at 500 °C in a Barnstead Thermolyne 62700 furnace for five hours after which they were weighed for a second time. Levels of soil organic matter (SOM) were reported as a percentage of total soil volume (% SOM), calculated for each sample using Equation 3 (Gavlak et al. 2005).

Equation 3:

$$\% \, SOM = \left[\frac{(105OvenWeight - 500MufflerWeight)}{105OvenWeight}\right] x \, 100$$

Soil carbon and nitrogen

Subsamples of soil samples were air-dried until they were constant weight and then passed through a 2 mm sieve. Three replicates of each dried, sieved sample, weighing between 10 to 15 mg, were folded into aluminum capsules. Prepared samples were then analyzed for levels of total carbon and total nitrogen using a ThermoScientific FlashSmart Elemental Analyzer. (Gavlak et al. 2005; ThermoScientific 2017)

Statistical analyses

All statistical analyses and figures were produced using R for Statistical Computing, version 1.4.1103 “Wax Begonia” (R Core Team 2021). In all cases, significance was defined by $p < 0.05$. Plant diversity, forage species composition, productivity, forage quality, and soil characteristic responses were compared between mowing treatments using mixed effect models from the “lme4” package. All models included block as a random value. Tukey’s HSD post hoc analyses were performed on all models using the “emmeans” package.

RESULTS

Weather, irrigation, and soil moisture data

A summary of collected weather, irrigation, and soil moisture data is displayed in Figure 2.7. Values are averaged for each month of the growing season, starting in May, and ending at the date of treatment application in August of each study year. Average temperature for each recorded month was seen to be higher in 2021 than in 2020 (Figure 2.7A). The maximum temperatures recorded for each study year were 35.05 °C on August 16th, 2020 and 41.56 °C on June 29, 2021. Total rainfall measured by the weather station (Figure 2.7B) was consistently higher in 2020 compared to 2021, with 2021 seeing less than 0.05 mm of rainfall each month. Figure 2.7C shows the approximate irrigation applied by the sprinkler system each month. In total, similar amounts of irrigation were applied within each study year, but the timing of application varied. In 2020, highest levels of irrigation were seen in June, with lower levels being applied throughout the remainder of the season. 2021 had highest levels of irrigation occurring in August. Soil moisture readings were generally higher in 2020 than in 2021 (Figure 2.7D). In May of 2020, VWC was 35.02 % with values gradually decreasing over time to reach 24.95 % in August. 2021 showed VWC values of 16.69 % in May, gradually increasing to 27.44 % in August.

2020 saw lower average temperatures and higher amounts of rainfall, causing higher soil moisture throughout the season. Rainfall was highest in August, resulting in less need for irrigation application later in the summer. 2021 was a much hotter and drier year, requiring higher amounts of irrigation earlier in the season, and overall lower soil moisture values.

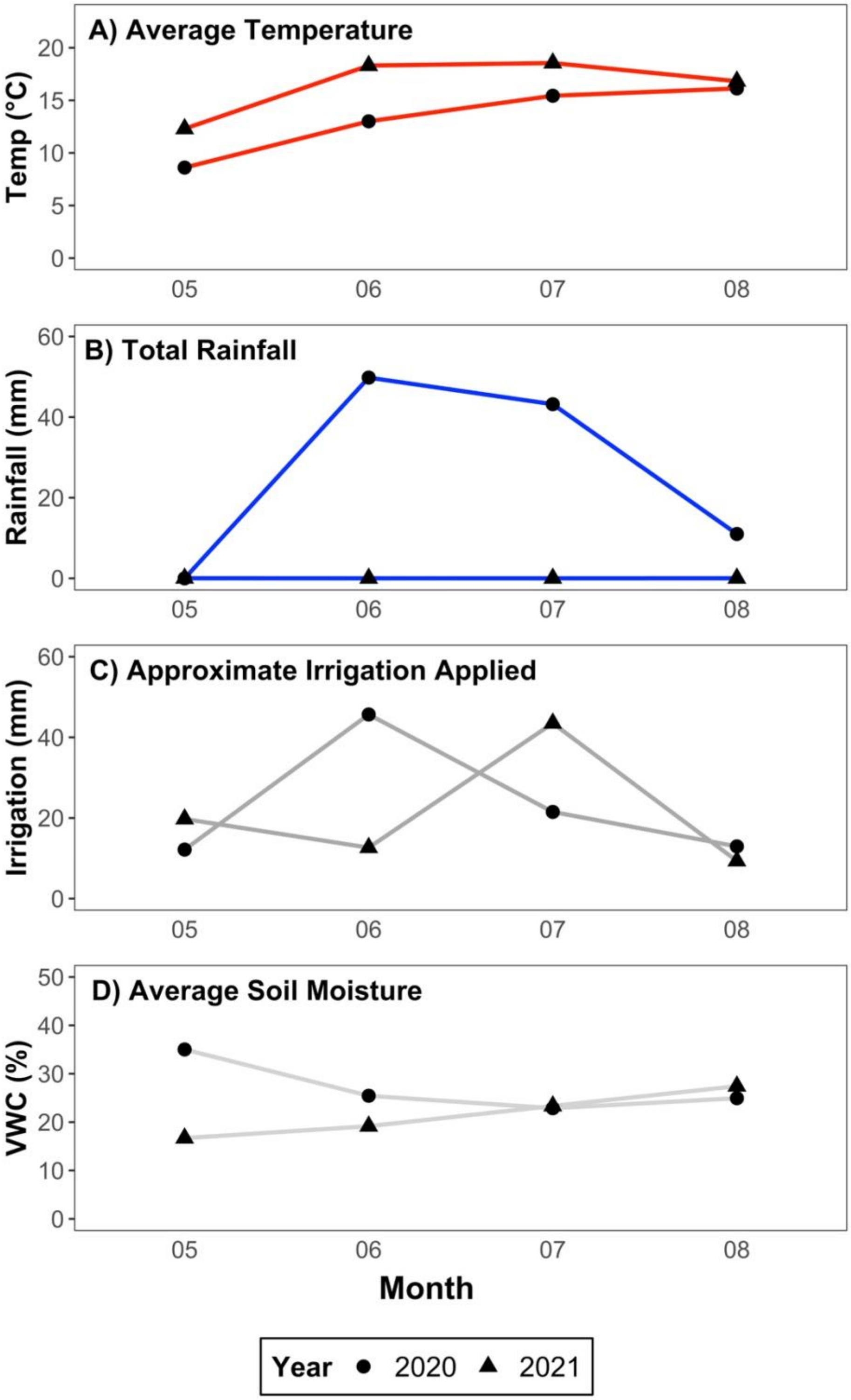

Figure 2.7: Summary of A) Average temperature, B) Total rainfall, C) Approximate irrigation applied, and D) Average soil moisture for the study enclosure May to treatment application in August throughout 2020 and 2021.

Plant community diversity and forage species composition

Measures of plant diversity were compared across mowing treatments between June 2020, before application of treatments, and August 2021, after three applications of treatments (Figure 2.8). Simpson's Diversity is not included in this figure as the results were similar to that of the Shannon -Weiner Diversity index. Prior to application of treatments in June 2020 (Figure 2.8A), no significant differences were found across study plots for Shannon-Weiner diversity and species richness. In August 2021 (Figure 2.8B), there were no significant difference across mowing treatments for Shannon-Weiner diversity ($F = 1.35$, $p < 0.05$). When comparing between June 2020 and August 2021 for this measure of diversity, it appears there is less variation in diversity after three applications of the mowing treatments. Species richness in August 2021 showed similarity between most treatments, except for M0 which had significantly lower richness than M15 ($F = 2.62$, $p = 0.0064$).

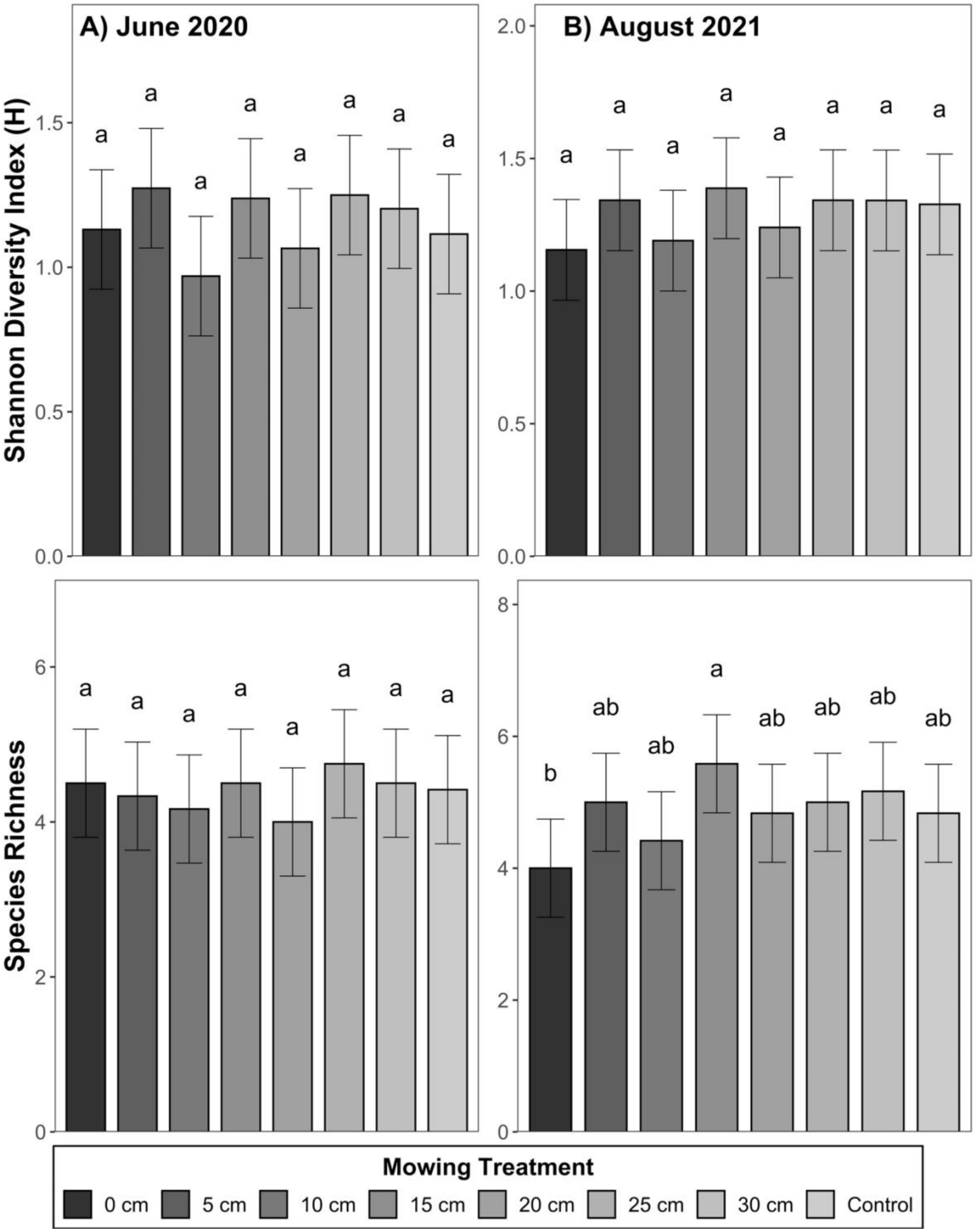

Figure 2.8: Values of Shannon-Weiner diversity and species richness across treatments plots in A) June 2020 prior to application of mowing treatments; and B) August 2021 after three applications of mowing treatments, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, n=12).

The plant community was surveyed for composition of seeded forage species found across mowing treatments throughout the duration of the study. Figure 2.9 shows a visual representation of the differences in cover seen for the three forage species at the different survey dates. Descriptive statistics were used to describe this figure. In both study years, across all treatments, there was a reduction in absolute cover of *P. pratense* from the surveys taken pre-mow in June to surveys recorded in August. Between June and August survey dates, the average cover of *P. pratense* reduced 11.45% and 19.22% in 2020 and 2021, respectively. After three treatment applications (August 2021, Figure 2.10D), the cover of *M. sativa* had increased within the lower mowing treatments. In August 2021, M0 plots had an average *M. sativa* cover of 51.67%, while control plots contained an average of 23.33% *M. sativa* cover.

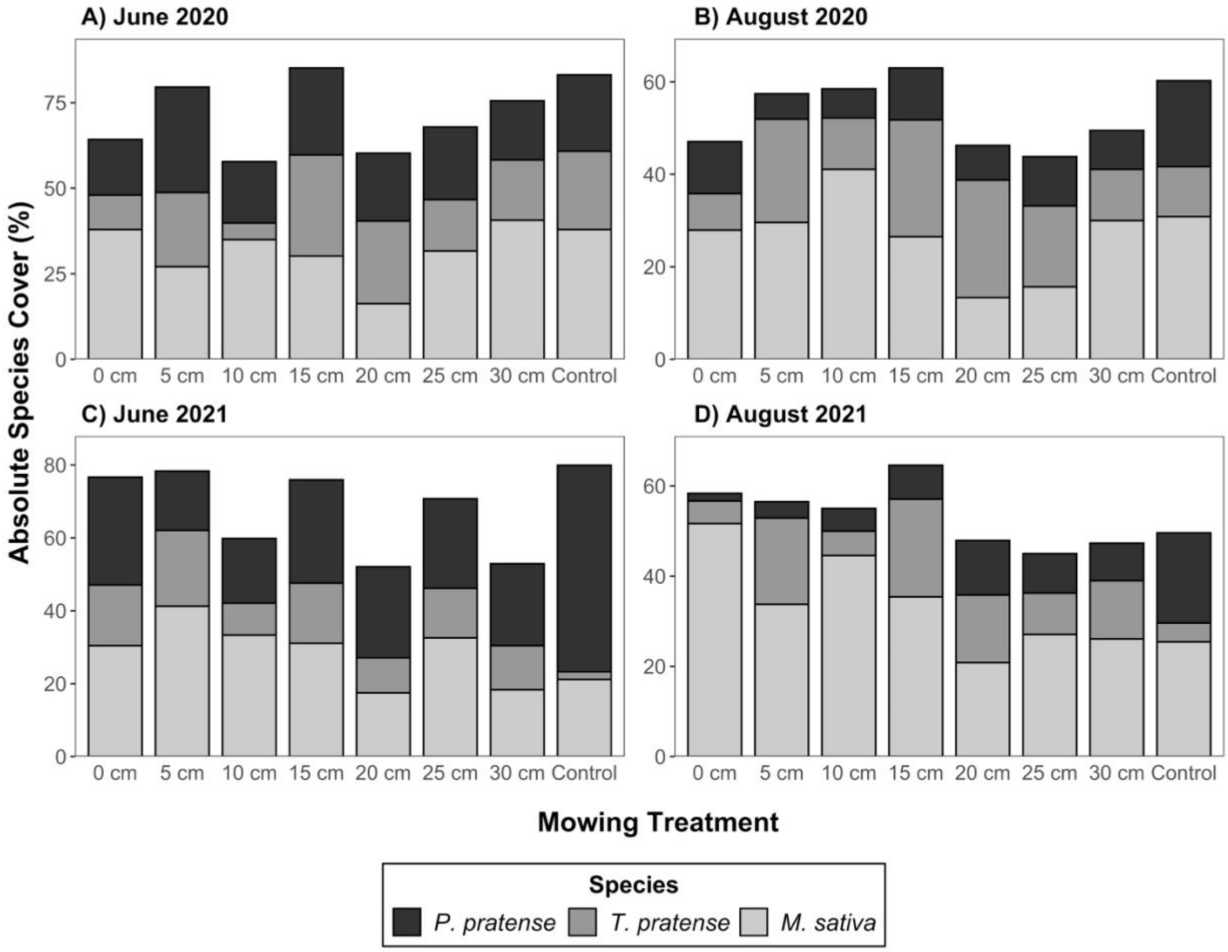

Figure 2.9:Average absolute percent cover of seeded forage species across mowing treatments recorded in A) June 2020, B) August 2020, C) June 2021, and D) August 2021, (n = 12).

To further examine differences in forage species cover, statistical comparisons were made. Average absolute species cover recorded for each forage species was compared at each survey date taken after mowing treatments had been applied (August 2020, June 2021, and August 2021). No significant differences were found at any survey date for cover of *T. pratense* between mowing treatments. Significant differences were seen at various survey dates for average absolute cover of *P. pratense* and *M. sativa.* See Table 2.4 for a list of comparisons that showed significant differences. In combination with the descriptive statistics described above for Figure 2.9 and the statistical differences seen in Table 2.4, results showed *P. pratense* cover decreased after mowing, with lower cutting heights producing the biggest cover reductions, and *M. sativa* cover increased after mowing, specifically at lower cutting heights.

Table 2.4: Summary table of forage species cover comparisons between mowing treatments at different survey dates showing F-value from ANOVA and p-value from Tukey HSD post-hoc analyses (n=12).

Timing	**Species**	**Treatment Comparison**	**F Value**	**P Value**
August 2020	*M. sativa*	M10 – M20	2.11	0.0353
	P. pratense	M5 – C	4.00	0.0012
		M10 – C		0.0012
		M20 – C		0.0103
June 2021	*P. pratense*	M0 – C	7.717	0.0112
		M5 – C		<0.0001
		M10 – C		<0.0001
		M15 – C		0.0055
		M20 – C		0.0001
		M25 – C		0.0013
		M30 – C		0.0002
August 2021	*P. pratense*	M0 – M15	8.413	0.0081
		M0 – M20		0.0088
		M0 – M25		0.0120
		M0 – M30		0.0062
		M0 – C		<0.0001
		M5 – C		<0.0001
		M10 – C		0.0002
		M25 – C		0.0456

Prior to each treatment application, photopoints were taken within each study plot to assess plant growth stage. Figures 2.10 through 2.13 show an irrigated study plot before treatment application in June and August of both 2020 and 2021. The photos taken pre-treatment application in June (Figure 2.10 and 2.12) showed *P. pratense* was in its flowering stage, with large seed heads apparent within the plot area. *M. sativa* was also shown to be in its budding to early flowering stage. In the August photopoints (Figure 2.11 and 2.13), the crops were observably more mature than they were at the June harvest event, with late-flowering *T. pratense* and *M. sativa* abundant throughout the plot.

Figure 2.10: Photopoint of study plot prior to treatment application in June 2020, red circles show examples of flowering *P. pratense*, yellow circles show examples of budding or flowering *M. sativa*.

Figure 2.11: Photopoint of study plot prior to treatment application in August 2020, orange circles show examples of late-flowering *T. pratense*, black circles show examples of late flowering or seed stage *M. sativa*.

Figure 2.12: Photopoint of study plot prior to treatment application in June 2021, red circles show examples of flowering *P. pratense*, yellow circles show examples of budding or flowering *M. sativa*.

Figure 2.13: Photopoint of study plot prior to treatment application in August 2021, the orange circle shows an example of late-flowering *T. pratense*, the black circle shows an example of late flowering or seed stage *M. sativa*.

Aboveground plant productivity

Mowing treatments showed significant differences in aboveground biomass collection in June (F=28.89, $p < 0.05$: Figure 2.14A) and August 2020 (F=19.74, $p < 0.05$: Figure 2.14B). For both sampling events, aboveground biomass decreased as cutting height increased, with highest levels of aboveground biomass seen at the lower cutting treatments of M0, M5 and M10. Similar trends were seen in 2021 for biomass collection in June (F=27.64, $p < 0.05$: Figure 2.15A) and August (F=12.79, $p < 0.05$: Figure 2.15B). In August of both sampling years, aboveground biomass collected from M10 treatment plots, though not significant, was slightly higher than the lower cutting treatments M0 and M5. For all collections of aboveground biomass, mowing treatments can generally be grouped by similar yield into low (M0, M5 and M10), moderate (M15 and M20), and high (M25 and M30) cutting height categories.

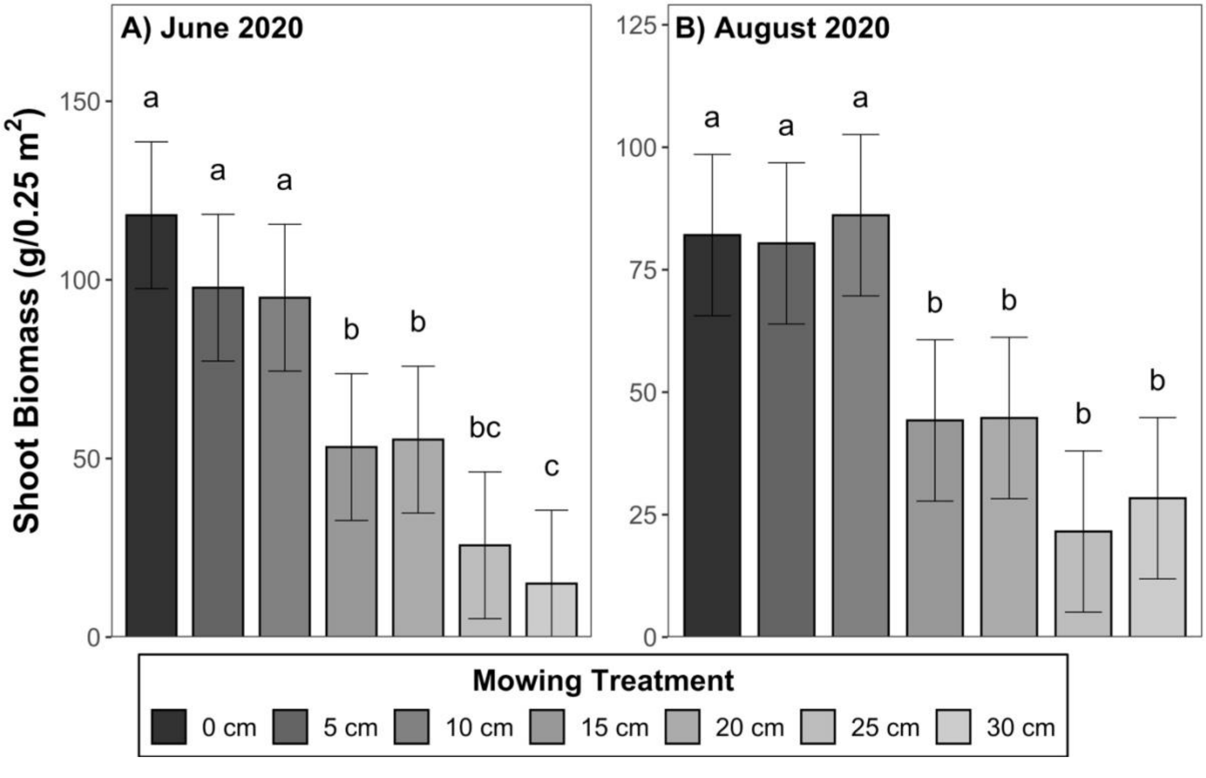

Figure 2.14: Biomass samples collected across mowing treatments in A) June 2020; and B) August 2020, comparisons made within months, error bars represent 95% confidence intervals, significant differences denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, n=12).

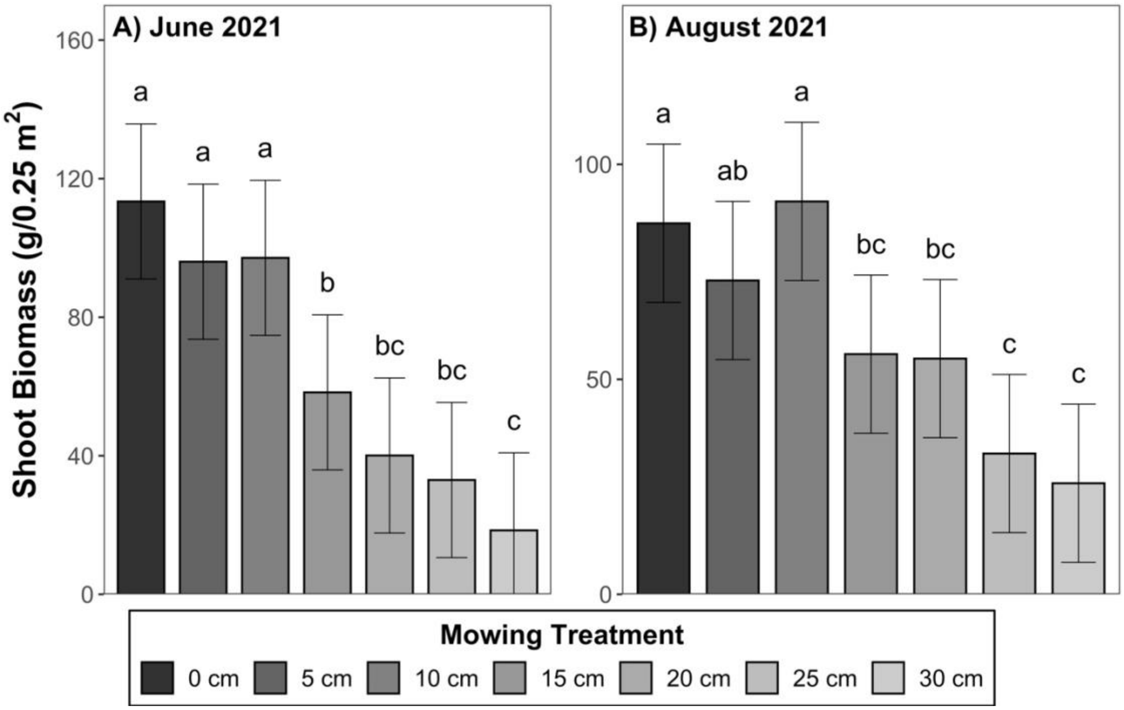

Figure 2.15: Biomass samples collected across mowing treatments in A) June 2021; and B) August 2021, comparisons made within months, error bars represent 95% confidence intervals, significant differences denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Significant differences were shown when comparing cumulative biomass harvested during the study duration across mowing treatments ($F=30.45$, $p<0.05$: Figure 2.16). Cumulative biomass was shown to be highest at the low cutting heights, decreasing as cutting height increased. The group of low mowing treatments produced significantly more biomass than all other treatments. When looking at the group of low mowing treatments, M10, though not significant, produced slightly higher levels of cumulative biomass than M0 and M5. Lowest amounts of cumulative biomass were seen in control plots.

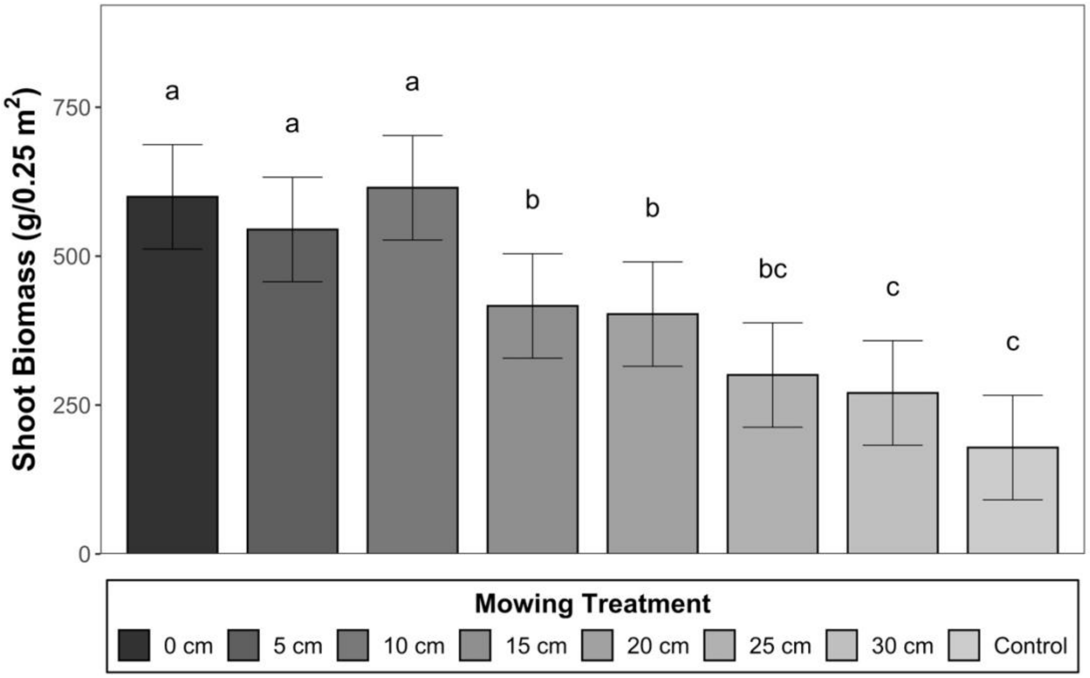

Figure 2.16: Cumulative biomass harvested across mowing treatments from June 2020 to August 2021, including final harvest to 0 cm, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Height measurements and two-month regrowth response

In June 2020, prior to application of mowing treatments, no differences in plant height were found across study plots ($F=2.15$, $p < 0.05$: Figure 2.17A). In August 2020, two months after the first application of mowing treatments, significant differences were shown in shoot height across treatments ($F=7.064$, $p < 0.05$: Figure 2.7B). The M0 plots showed the lowest average plant height, and were significantly shorter than M10, M20, M25, and control plots. Control plots showed the highest average plant height of all treatments. A better estimation of productivity differences between treatments is given when looking at the two-month regrowth response, from treatment application in June to pre-treatment measurements in August (Figure 2.17C). Significant differences are exhibited for two-month regrowth response across mowing treatments ($F=34.68$, $p < 0.05$). This response was shown to be highest at low cutting heights, trending downwards as mowing height increased. The group of low cutting heights (M0, M5, and M10) all were significantly more productive than treatments higher than M15. Control plots, which had the highest August shoot height, showed the lowest two-month regrowth response of all treatments.

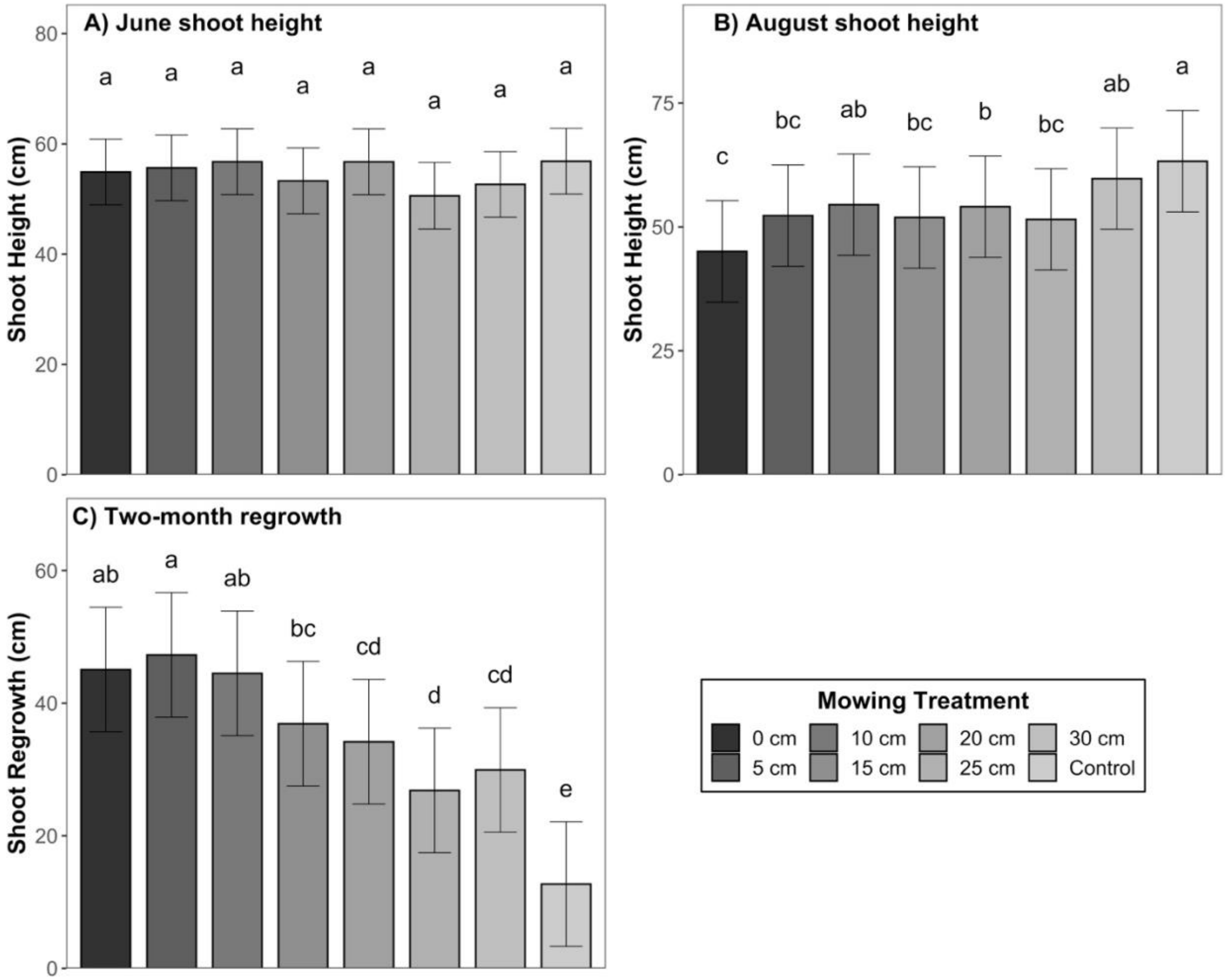

Figure 2.17: Aboveground productivity across mowing treatments predicted by plant height: A) Shoot height in June 2020, prior to application of mowing treatments; B) Shoot height in August 2020, two months after first application of mowing treatments; C) Amount of regrowth from June 2020 mowing event, measured by subtracting mowing treatment height from August shoot height, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Figure 2.18A shows shoot height measured in June 2021, after two prior applications of mowing treatments throughout 2020. Significant differences were found in height measurements across treatments ($F=7.94$, $p < 0.05$), with the low cutting treatment resembling the shortest shoot heights. Similar results were seen in August 2021, when shoot height was measured after the application of treatments in June 2021($F=5.208$, $p < 0.05$: Figure 2.18B). The two-month regrowth response for 2021 (Figure 2.18C) showed similar results to 2020. Productivity was significantly higher at lower cutting heights, decreasing as cutting height increased (F=43.50, $p < 0.05$). Control plots again showed the lowest regrowth response of all treatments.

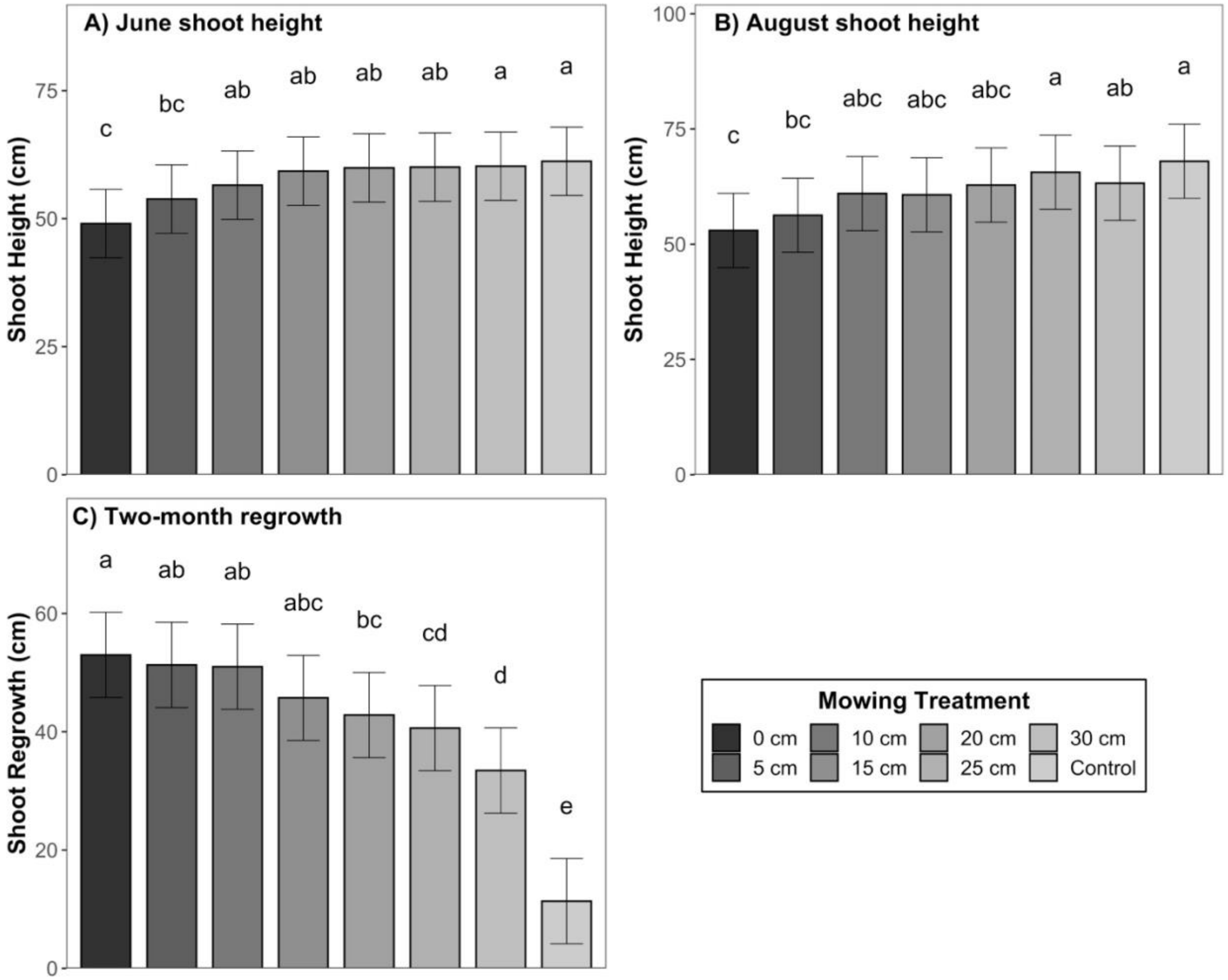

Figure 2.18: Aboveground productivity across mowing treatments predicted by plant height: A) Shoot height in June 2021, prior to application of mowing treatments in 2021; B) Shoot height in August 2021, two months after third application of mowing treatments; C) Amount of regrowth from June 2021 mowing event, measured by subtracting mowing treatment height from August shoot height, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Belowground plant productivity

Belowground plant productivity, estimated by measures of root biomass, was not significantly different across mowing treatments in 2020 or 2021 (Figure 2.19). As there were no significant differences between mowing treatments, root biomass was grouped by treatment and compared between years. Across all treatments, 2020 saw significantly higher levels of root biomass than 2021 (F = 24.16, $p < 0.001$, n = 96).

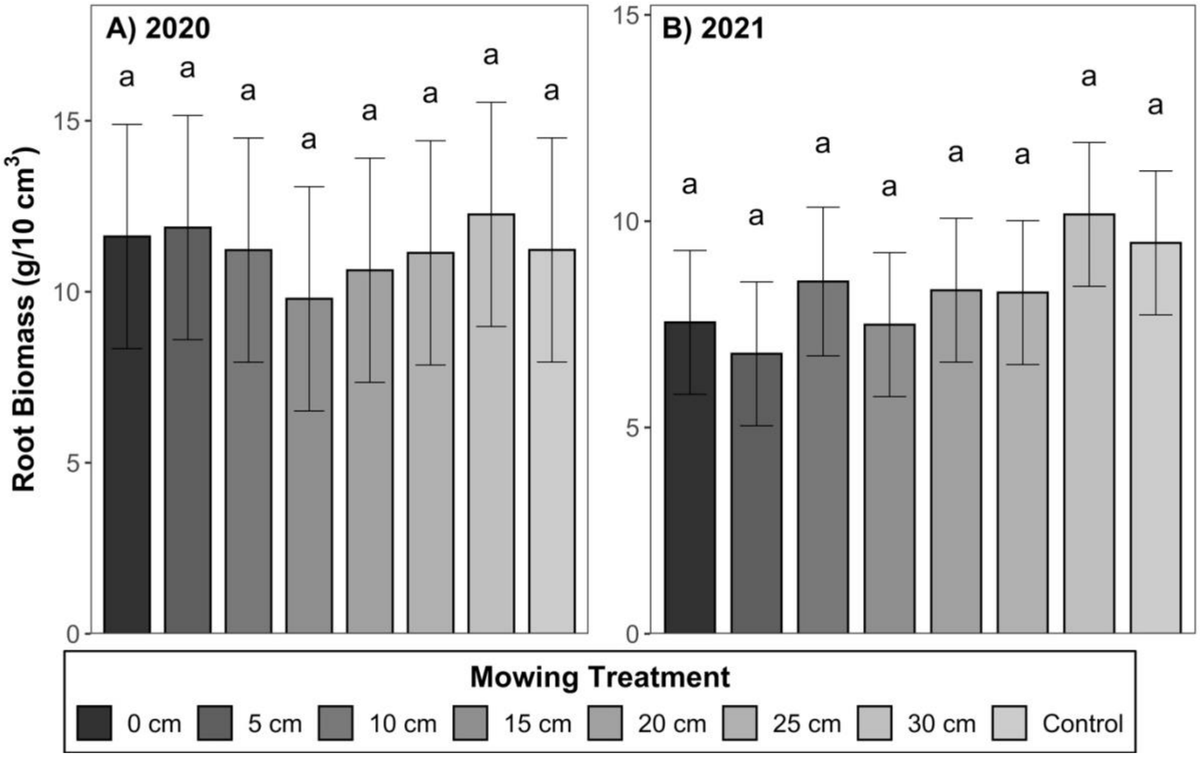

Figure 2.19: Belowground plant productivity estimated by root biomass across mowing treatments collected in A) September 2020 and B) August 2021, comparisons made within years, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, n=12).

Forage quality

Forage quality was compared between samples collected for M0 and M30 treatments in June and August of 2020 (Figure 2.20). In June 2020, M30 samples were significantly higher in crude protein (F =46.097, p = <0.0001) and soluble protein (F = 28.335, p = <0.0001) and were significantly lower in ADF (F =2.951, p = 0.0015).When comparing M0 and M30 in August 2020, M30 treatments showing significantly higher levels of crude protein (F =46.097 , p = 0.0034), lignin (F =7.613 , p = 0.0008), and lower values of TDN (F =2.233, p = 0.0027).

Figure 2.20 also compares forage quality between June and August sample collection dates. M0 samples collected in June showed significantly higher levels of crude protein (F = 32.729, p =0.0258) and significantly lower values of TDN (F = 4.501, p = 0.0008) than M0 samples collected in August. M30 samples collected in June showed significantly higher levels of crude protein (F = 32.729, p = <0.0001) and soluble protein (F =29.442, p = <0.0001) and lower values of ADF (F = 15.534, p = 0.0120) and lignin (F =1.803, p = 0.0129).

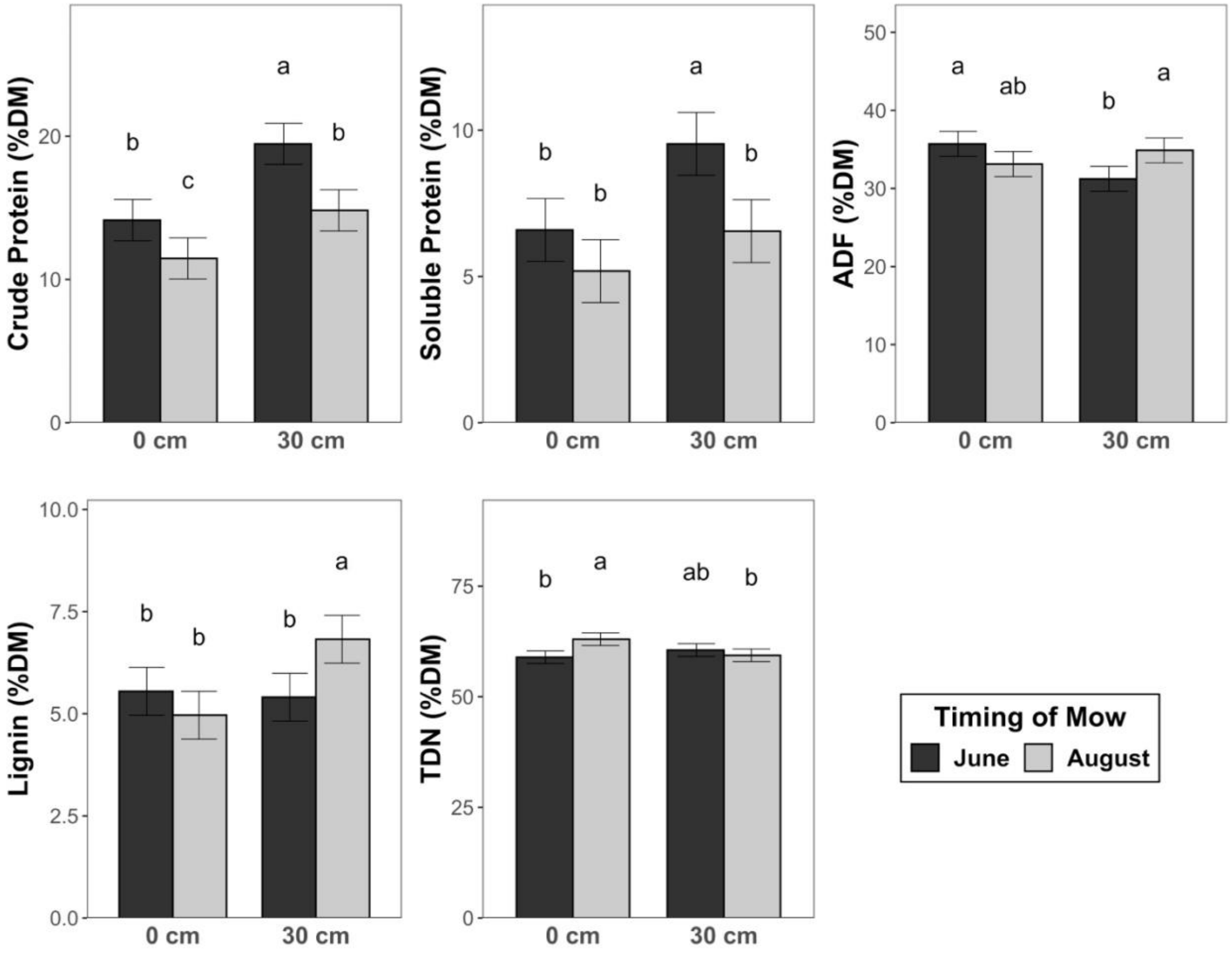

Figure 2.20: Comparison of forage quality between 0 cm and 30 cm biomass samples collected in June and August of 2020, error bars represent 95% confidence intervals, significant differences denoted by different lowercase letter as determined by post-hoc Tukey test following ANOVA ($p < 0.05$, n=12).

In 2021, samples were only analyzed for forage quality in June, comparing M0 and M30 (Figure 2.21). M30 samples showed significantly higher levels of crude protein (F = 27.98, p = 0.0001), soluble protein (F = 19.09, p = 0.004) and TDN (F = 7.359, p = 0.0148), and significantly lower values of ADF (F = 21.79, p = 0.002) than M0 samples.

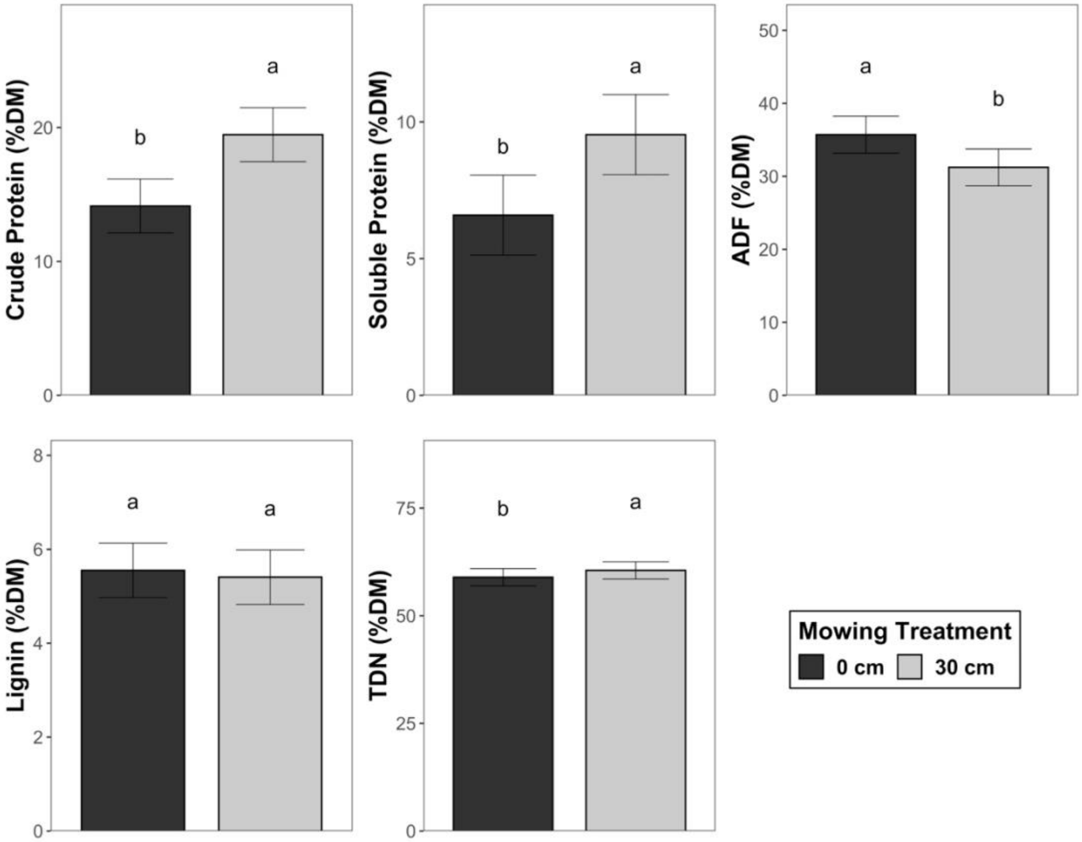

Figure 2.21: Comparison of forage quality between 0 cm and 30 cm biomass samples collected in June and 2021, error bars represent 95% confidence intervals, significant differences denoted by different lowercase letter as determined by post-hoc Tukey test following ANOVA (p<0.05, n=12).

Soil carbon, nitrogen, and organic matter

Soils collected in August 2021 were analyzed for levels of total carbon, total nitrogen, and soil organic matter. Figure 2.22 shows a comparison between mowing treatments for these three soil variables. M10 was shown to have greater values of both total carbon (F= 4.73, p < 0.05: Figure 2.22A) and total nitrogen (F = 4.346, p < 0.05: Figure 2.22B) than M15, M25, M30, and control treatments. Figures 2.22A and 2.22B also show that M15 had significantly lower values of total carbon and total nitrogen than the M10 and M20. Generally, the low cutting heights show higher values of total carbon and nitrogen than the moderate and high cutting heights. Soil organic matter, shown in Figure 2.22C, was found to be significantly higher at M10 than at M0, M5, M15, and M30 (F = 3.653, $p < 0.05$). For all soil variables shown in Figure 2.22 (total carbon, total nitrogen, and soil organic matter), highest values are shown within M10 treatment plots.

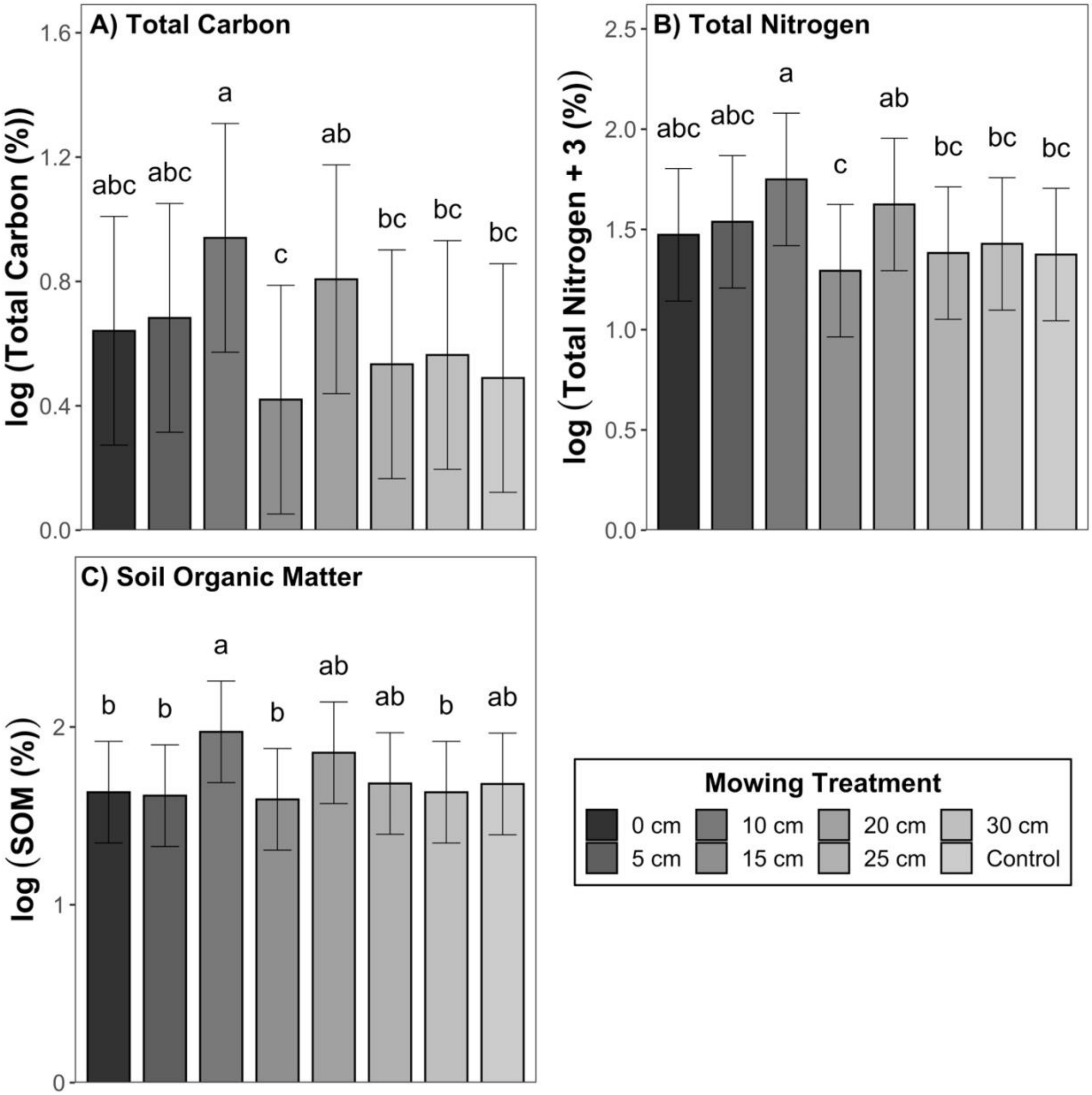

Figure 2.22: Comparison of soil metrics across mowing treatments collected in August 2021 at a depth of 0 to 15 cm; A) Total Carbon; B) Total Nitrogen; and C) Soil Organic Matter, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

DISCUSSION

Weather, irrigation, and soil moisture data

The Chilcotin region is characterized by hot and dry summers (Cariboo-Chilcotin Coast – Overview 2021). These characterizations were confirmed by the weather data recorded throughout the growing seasons of 2020 and 2021. Both years showed high levels of temperature and low levels of precipitation. 2021 experienced virtually zero rainfall throughout the summer months and extreme heat for prolonged periods, representing a drought year. These conditions were contradicted through the application of irrigation to the cropping system from May to August of each year. This supplemental moisture increased VWC of the soil, allowing for the successful production of the cropping system consistently throughout the duration of the study.

Plant community diversity and forage species composition

Mowing has been shown to decrease or increase diversity depending on intensity (Li et al. 2021; Yang et al. 2020; Wan et al. 2016), however it was not found in the experiment presented here. Mowing treatments did not change levels of plant diversity throughout the study's duration. Prior to application of mowing treatments, there was inherent variation seen across study plots, most of which was not significant. Surveys recorded in August 2021, after three treatment applications, again showed inherent variation across treatments with no notable significant differences. Current management goals and previous management history of the study area are likely responsible for the consistent levels of diversity seen throughout multiple treatment applications.

Management goals of perennial cropping systems tend to focus on productivity rather than species diversity and thus are typically seeded with either monocultures or simple grass-legume mixtures (Sanderson et al. 2013). Species are selected for their relative yield, nutrient content, and adaptability to environmental conditions (Milić et al. 2019). The success of a forage system is determined by the high cover and yield of seeded forage species, rather than levels of biodiversity. Invasion of unseeded, unpalatable species, which may increase diversity, are unwanted in these systems and can represent a reduction in either crop or nutrient yield (Bittman et al. 2013). The species composition of the study site reflects this goal, with a high cover of seeded forage species, and relatively low cover and abundance of other species.

Management practices applied to established perennial cropping systems can further promote the success of desired forage species. Irrigation and fertilization have been consistently used at the study site and are likely attributing to the success of seeded species. These practices help to decrease water and nutrient restrictions, ultimately increasing biomass production. The combination of these techniques has been shown to decrease levels of species diversity (Müller et al. 2016). In this cropping system, diversity is maintained through the success and abundance of seeded forage species.

Along with yield and nutritive value, forage crops are often selected for their ability to respond to mowing. Mowing is a necessity to harvest forage, making response to mowing an important factor in forage yield (Wang et al. 2014). The different forage species within this cropping system show different regrowth responses following treatment application. *P. pratense* shows a negative response to mowing, represented by a decrease in cover across all treatments for vegetation surveys taken in August 2020 and 2021, two months after the first harvest of each season. *P. pratense* is known to exhibit slow regrowth after defoliation at certain growth stages due to damaging or removal of bulblets, which are formed in the spring and contain important nutrient reserves (Ogle et al. 2011). When treatments were applied in late-June of each study year, *P. pratense* plants were already producing seed heads, and therefore past the bulblet-producing growth stage, resulting in a poor regrowth response. Yields of *P. pratense* can be further reduced during mid-summer by hotter and drier conditions due to their shallow root systems (Bittman et al. 1999). This is likely the reason for a greater decline in *P. pratense* in 2021, as the season was hot and dry, and saw decreased levels of soil moisture following treatment application in June. Cover of *P. pratense* was further declined from June to August of 2021 within the low mowing treatments. Because this species responds poorly to defoliation, it is recommended to use a cutting height higher than 10 cm, this helps preserve the growing points of the grass and maintain stands of *P. pratense* (Bittman et al. 1999; Ogle et al. 2011), which is seen within study plots with higher cutting heights applied.

Opposite to *P. pratense*, *M. sativa* saw a positive response to mowing, with cover increasing after treatment application in June within both study years. Cutting timing and height are both important variables that can affect yields of *M. sativa* (Milić et al. 2019). In June of both 2020 and 2021, *M.*

sativa within study plots was at its bud to early flower stage. When harvested at this growth stage, plants have built up sufficient carbohydrate reserves within their roots and will exhibit a strong regrowth response (Undersander et al. 2011). Yields of *M. sativa* have been shown to further increase when using a cutting height under 5 cm. When cut at such a low height, the axillary buds are removed, forcing growth to come from crown buds of the plant (Wiersma et al. 2007). Stems originating from crown buds contribute more towards total yield than stems originating from axillary buds (Wolf and Blaser 1981). This is likely the effect seen in this study, with highest *M. sativa* cover seen at lower cutting heights.

Aboveground plant productivity

Mowing is shown to produce a compensatory growth response and stimulate plant productivity, both in this study and those previous (Wan et al. 2016; Han et al. 2014; Wang et al. 2014; Turner et al. 1993; Dyer et al. 1991). Lowest aboveground productivity, throughout both study years, was seen in control plots. These unmowed plots showed both the lowest levels of cumulative biomass and regrowth response compared to any of the mowing treatments. This disparity in productivity is likely due to the absence of a compensatory growth response as these plots did not experience any defoliation throughout the study’s duration. This shows that while mowing is often a necessary practice for agricultural operations, it is also beneficial to help increase plant productivity through the mechanism of compensatory growth.

A plant’s regrowth response to mowing, or degree of compensatory growth, is important for the continued plant production and hay yield of a cropping system (Wang et al. 2014). Compensatory growth, and overall aboveground plant productivity, have been shown to vary with mowing intensity and degree of defoliation (Yang et al. 2020; Wan et al. 2016; Wang et al. 2014; Zhao et al. 2008; Huhta et al. 2003; Turner et al. 1993), an effect which was also seen in this study. Aboveground plant productivity, estimated by shoot biomass and regrowth response, was shown to be highest at low mowing heights, with productivity trending downwards as mowing height increased. M0, M5, and M10 appeared favourable for a high yielding first harvest in June, stimulating the maximal compensatory growth response for a second high yielding harvest in August. Higher mowing treatments (M15 through M30) lacked biomass at both June and August sampling events and showed a lower regrowth response in both 2020 and 2021. These findings do not support our hypothesis. We predicted that maximal compensatory growth would be seen at cutting heights greater than 10 cm and less than 20 cm. This study showed that cutting heights equal to or less than 10 cm produced increased levels of compensatory growth.

Along with not supporting the hypothesis, the differences in aboveground productivity seen between mowing treatments contradicts the findings of many previous studies which closely examined cutting heights (Yang et al. 2020; Wan et al. 2016; Wang et al. 2014; Zhao et al. 2008; Huhta et al. 2003; Turner et al. 1993). Each of these studies identified a moderate mowing height, ranging from 14 to 24 cm, to produce highest levels of aboveground productivity. In some cases, mowing heights below 14 cm (Yang et al. 2020) or 6 cm (Zhao et al. 2008) decreased biomass production to less than that of unmowed plots, further contradicting this study's results. These previous studies have been performed in both natural and controlled, irrigated environments but examined much different plant species. Reasons behind these results opposing others are likely crop specificity and current management regimes, as these both affect how a cropping system will respond to mowing (Huhta et al. 2003).

All plants greatly vary in how they respond to defoliation (Huhta et al. 2003). The main components of this study's cropping system were *P. pratense*, *T. pratense*, and *M. sativa*. While *P. pratense* regrows best at heights above 10 cm (Ogle et al. 2011), both *T. pratense* and *M. sativa* respond better to lower cutting heights, yielding a higher regrowth response when a cutting height less than 5 cm is used roots. The ability to respond to heavy defoliation and large reductions in photosynthetic capacity is attributed to carbohydrate reserves with legume tap roots, which are allocated towards the new production of photosynthetic material (St. John and Ogle 2008; Wiersma et al. 2007). These two legume species make up the majority of the plant community throughout the study area, resulting in a cropping system that responds best to lower cutting heights. M10 was likely found to be the most productive treatment as this cutting height favours the regrowth of all three forage species. A 10 cm cutting height is low enough to stimulate increased regrowth in *T. pratense* and *M. sativa* but is high enough to retain carbohydrate reserves required for *P. pratense* regrowth, which are stored in aboveground plant tissue. While cutting heights shorter than 10 cm may further increase legume production, they also decrease *P. pratense* production, resulting in lower total yields in M0 and M5 compared to M10.

Current management practices in place at the study site, irrigation and fertilization, likely also influenced the cropping system's response to mowing. Each of *P. pratense, T. pratense, and M. sativa* are adapted to irrigation and produce higher yields under moist conditions (St. John and Ogle 2008; Ogle et al. 2011; Undersander et al. 2011). The fertilization combination of nitrogen, phosphorus, and potash annually applied to this cropping system also facilitates high yields at first and second harvest. Phosphorus and potash editions to the soil are required for successful growth of legume species (St. John and Ogle 2008; Undersander et al. 2011). These elements promote root development which is important for carbohydrate storage and regrowth responses in *T. pratense* and *M. sativa* (Undersander et al. 2011). The nitrogen component of the fertilizer aids the growth of *P. pratense*, allowing it to compete with the legume species during the early growing season (Ogle et al. 2011). The irrigation and fertilization management in place for this cropping system provides the necessary water and nutrients required for each species to be highly productive and produce a compensatory growth response to mowing. In areas where moisture or nutrients are more limited, there would likely be a different response to mowing.

Belowground plant productivity

Healthy root systems of agricultural crops are important for water and nutrient storage and absorption, and regrowth following mowing (Wang et el. 2014). Along with crop benefits, root systems also represent a large carbon pool, and thus contribute environmental benefits through carbon storage (Harrower et al. 2012; Ferraro and Oesterheld 2002). Aboveground and belowground productivity are dependent upon each other, and thus is it important to understand how practices that effect aboveground productivity, like mowing, also effect belowground productivity (Breulmann et al. 2012). In this study, mowing was not found to affect levels of root production. This is peculiar as aboveground productivity has been suggested to have a direct linear relationship with belowground productivity (Harrower et al. 2012), which suggests the results of productivity highest at lower heights, and steadily decreasing as cutting height increased.

When considering the relationship between aboveground and belowground productivity, defoliation intensity should be taken into consideration. In this study, defoliation intensity was varied by clipping at different heights, which could have affected the proportion of aboveground to belowground regrowth response. When defoliation occurs, aboveground regrowth is produced through ongoing photosynthesis. To assist regrowth, allocation of photosynthesis products is likely to shift towards the aboveground production of leaves, favouring increased rates of photosynthesis and thus further regrowth (Oesterheld et al. 1992). As the intensity of defoliation increases, the proportion of aboveground to belowground productivity can also be expected to increase (Oesterheld et al. 1992), which is occurring in the results presented here. Lower cutting heights appear to be slightly lower in root production compared to higher cutting height and control treatments. This is likely due to increased defoliation intensity causing a shift in photosynthetic allocation towards aboveground productivity within the lower mowing treatments. Of the low mowing treatments, M10 produced the highest mean root biomass, which correlates with values of aboveground productivity seen. In this case, it appears as though the equivalence of aboveground and belowground productivity are more linearly related than that of treatments with a higher defoliation intensity (M0 and M5), making M10 the favourable treatment for combined aboveground and belowground productivity. It should be noted that although there are trends in the data, there were no significant effects of mowing treatment on root biomass levels. Therefore, the low cutting heights which produce large yields of aboveground biomass can be said to produce levels of root biomass equivalent to that of higher cutting height and control treatments. It is hard to draw strong conclusions on the response of belowground productivity due to the high variability within treatments resulting in a lack of significance. To reduce variability and better understand this response, sampling protocols must be improved to reduce possible inaccuracies due to root loss. Increasing the number of collected root biomass samples would also help to reduce variability, creating a more representative sample of both taproot and fibrous root systems.

Environmental conditions can also play a role in belowground productivity. The two study years had quite different environmental conditions which could be responsible for the discrepancy between average root biomass levels in 2020 and 2021. Water limitations and heat stress are both factors which can limit aboveground and belowground productivity. When limited by water, plants shift focus to root production rather than leaf production (Hsiao and Xu 2000). Our results contradicted this, showing lower root biomass and equivalent shoot biomass, when comparing dry to wet years. Irrigation of the field site is likely the explanation for this contradiction. Although there was very little rain in 2021, irrigation occurred throughout the growing season, resulting in soil moisture values that were similar to that of 2020. Along with little precipitation, 2021 also saw high temperatures throughout the growing season. Heat stress has been shown to negatively impact root development of agricultural crops (Irmak 2016), reducing overall root productivity. As such, it is likely that the extreme heat experienced throughout 2021 is responsible for the decreased root biomass seen across treatments in this study year.

Forage quality

Along with forage yield, forage quality is another important variable that concerns producers. Having high quality forage both increases the value of a crop and potential animal performance (Ball et al. 2001). Forage quality can be described in many ways. In this study, we examined nutrient content of different forages to estimate overall forage quality. Cutting height was shown to affect forage quality, with higher cutting heights producing forage of higher quality. Overall, M30 forage had higher crude protein, soluble protein, and TDN, along with lower ADF values than M0 forage. Cutting height has been previously shown to change forage quality, specifically in *M. sativa*-dominated crops. Lower stems of *M. sativa* contain fewer high-quality leaves than stems higher up on the plant (Wiersma et al. 2007). When a higher cutting height is used, harvesting of the lower stems is avoided and only the upper stems of the plant are collected, increasing overall forage quality (Wiersma et al. 2007). As the study crop contains a high cover of *M. sativa*, this is likely the reasoning for different qualities of forage seen here. However, there is the argument for yield versus quality. When cutting a crop at lower cutting heights, higher yields are produced than when leaving a higher stubble height, effects seen in this study. This high yield of forage includes both lower and upper stem segments of *M. sativa*. High-quality upper stems are still present in M0 forage, but the quality is diluted by the addition of the lower stem segments, representing a trade-off between forage yield and forage quality. When determining at what height to harvest a crop, producers should consider both their desired yield and quality. If they are producing feed for animals that have lower nutrient requirements (i.e., beef cattle versus dairy cattle), perhaps it is not necessary to have higher forage quality and the smarter management decision would be to harvest for increased yield at a lower cutting height (Undersander et al. 2011).

Timing of harvest was also seen to effect forage quality. Samples collected in August of 2020 were lower in quality than those collected in June 2020 for both M0 and M30 samples. When a crop is harvested is one of the biggest determinants of forage quality as plants will have different nutritive values throughout their various growth cycles (Milić et al. 2019). *T. pratense* and *M. sativa* both produce higher quality forage when they are in their early-bloom phase, with decreased forage quality seen when plants reach maturity (St. John and Ogle 2008; Undersander et al. 2011). This effect explains the difference in forage quality seen between June and August 2020. At the timing of the June harvest, these two legume species were in their early-bloom phases, with several *M. sativa* flowers just beginning to emerge. At this early growth stage, leaf weight is greater than stem weight, and forage quality is high (Undersander et al. 2011). In August, *T. pratense* and *M. sativa* were both seen to be in their late bloom to seed phase at time of harvest. Once the plants are this mature, forage quality is decreased, mostly due to an increase in stem content of the forage (Undersander et al. 2011). Another reason for a decline in August forage quality is the absence of *P. pratense* at this harvest event. *P. pratense* is a highly palatable and nutrient-rich grass (Ogle et al. 2011), however it was seen to decrease in cover later in the growing season, not contributing towards the quality of the August forage as it may have in June. When managing crops for forage quality, producers should consider their harvest goals, taking into consideration both height and timing of cut in order to produce a crop that meets their specific yield and quality needs.

Soil carbon, nitrogen, and organic matter

Across the agricultural industry, management goals aim to achieve increased soil carbon as an attempt to combat greenhouse gas emissions through carbon sequestration (Conant et al. 2001). Changes in plant productivity typically correlate with changes in soil carbon, as aboveground productivity is a primary source of soil carbon (Kunkel et al. 2011). Therefore, management techniques that affect productivity can also be used to influence levels of soil carbon (Greenhouse Gases and Agriculture 2020). Mowing has been shown to effect plant productivity, however most short-term studies do not take account of the direct correlation between mowing and soil variables as soil takes longer to respond to management changes than the plant community (Yang et al. 2020). Surprisingly, we saw a change in soil characteristics in response to mowing height in just two seasons of treatment applications. The M10 treatment saw increased levels of soil carbon, nitrogen, and organic matter compared to all other treatments. These increases are likely due to the improvements in aboveground and belowground productivity also seen for the M10 treatment. These results further reinforce the correlation between plant productivity and soil carbon that has been seen in previous studies (Donovan 2013; Harrower et al. 2012; Kunkel et al. 2011; Conant et al. 2001).

Increases in aboveground productivity represent an increase in the amount of carbon dioxide that is being removed from the atmosphere, as it is used to produce, and is stored within, new leaf and shoot material (Greenhouse Gases and Agriculture 2020). This newly produced aboveground material also represents increases in carbon and nitrogen additions to the soil through root growth (Donovan 2013) and nitrogen-fixation by legume species (Conant et al. 2001). Increases in plant productivity are translated into increases in soil carbon through the process of decomposition (Abraha et al. 2018). The decomposition of plant material to soil carbon can be a slow process and is dependent on environmental factors, thus levels of decomposition can limit levels of carbon sequestration (Yang et al. 2020). Rates of decomposition can be increased by irrigation promoting microbial activity (Arroita et al. 2013). The irrigation of the study site, while increasing overall plant productivity, also helped speed rates of decomposition, allowing the high productivity seen at a 10 cm mowing height to also be seen within levels of soil carbon for this mowing treatment.

Measures of plant productivity and soil carbon are direct predictors of carbon sequestration occurring on a landscape (Conant et al. 2003). The changes in both of these variables seen at different mowing heights suggests potential for mowing to influence levels of carbon sequestration. Studying the aboveground and belowground responses together have allowed for the complete evaluation of mowing as a technique applied to perennial cropping systems (Breulmann et al. 2021).

CONCLUSION

This study has shown that mowing is an important tool for the management of perennial cropping systems. This technique has the ability to alter plant productivity and forage species composition, forage quality, and soil characteristics. Furthermore, this study has shown that the intensity of mowing applied can have differential effects on each of the previously mentioned variables.

Utilizing a 10 cm mowing height has been shown to be favourable for increased levels of aboveground and belowground productivity, and overall increases in soil carbon. These findings suggest that mowing is not only a method to harvest forage crops but can also be used for mutual benefits to producers and the environment through increased production and carbon sequestration. Future research should examine the effects of continued application of mowing treatments to ensure the results seen in this study continue over time. Additionally, species-specific biomass samples should be taken in order to further asses the effect of mowing height on forage species composition. Because of the array of possible responses to mowing, it is important not to apply the results of one study to an area with different environmental conditions. To best manage the mowing of agricultural crops, within B.C., we must gain a comprehensive understanding of plant response, including different species throughout different climates of the province.

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Chapter 3 - LONG-TERM EFFECTS OF ABANDONMENT OF IRRIGATION AND FERTILIZATION ON PLANT COMMUNITY DYNAMICS, PRODUCTIVTY, AND SOIL CHARACTERISTICS OF PERENNIAL CROPPING SYSTEMS

INTRODUCTION

Management history often determines agricultural land's productivity, plant community dynamics, and soil characteristics. Proper management can help increase aboveground and belowground plant productivity, soil fertility, nutrient availability, and carbon storage (Alavaisha et al. 2019; Ziter and Macdougall 2013). In contrast, poor or improper land management can decrease these same metrics, potentially resulting in unwanted changes in plant community dynamics. As a result, how land is managed has potential to affect plant diversity and productivity, soil characteristics, and rates of carbon sequestration.

Throughout British Columbia (B.C.), agricultural land is commonly managed using a combination of irrigation and fertilization. These practices are known to increase forage production and soil carbon and are considered 'management improvements' (Conant et al. 2001). The practice of irrigation involves the application of water to cropland to account for moisture deficits. Due to lack of rainfall during the growing season, this practice is often required in drier regions of the province to optimize crop production (Commodity 2014). Through increased plant productivity, irrigation introduces other benefits to cropland as well. Increased primary production, escalated by irrigation, equates to an increase in carbon dioxide sequestration within plant biomass (Arroita et al. 2013). This elevated biomass production also increases inputs of organic matter into the soil, contributing to the land's carbon stock (Alvaisha et al. 2019). The breakdown of this organic matter is facilitated by irrigation through increased microbial activity, for which moisture is a limiting factor (Arroita et al. 2013). This makes irrigation a suitable way to increase crop production while also mitigating environmental impacts through carbon sequestration (Alvaisha et al. 2019). Like all management techniques, if not utilized properly, irrigation can negatively impact landscapes. Irrigation regimes should be selected based on the areas' environmental conditions and water storage capacity (Farm Practice 2014a). Irrigation that is improperly applied can disrupt the hydrological regime (Arroita et al. 2013), cause soil drainage problems (Farm Practice 2014a), and influence changes in plant diversity (Müller et al. 2016). It is important that irrigation is used properly as a management technique to maximize possible benefits and minimize environmental deficits.

Fertilization is another management technique used in agriculture to increase production. Fertilizers work to increase nutrient availability by providing essential elements for plant productivity (Farm Practice 2014b). Fertilizers can be both organic (agricultural by-products) or inorganic (synthetic compositions of nutrients). By adding fertilizer to agricultural land, an increase in nutrient availability enables plant productivity (Alavaisha et al. 2019). As with irrigation, this increased productivity correlates with levels of soil organic matter and carbon sequestration (Alavaisha et al. 2019; Ziter and Macdougall 2013; Conant et al. 2001). However, through improper use, fertilization can result in increased nitrous oxide emissions (Conant et al. 2001), reduced biodiversity (Müller et al. 2016), pollution of soil and nearby aquatic ecosystems (Arroita et al. 2013) and soil acidification (Soil Factsheet 2015). Care should be taken while selecting and applying fertilizer to ensure proper practices are followed.

Research and farming practices have shown that irrigation and fertilization can alter land. The addition of irrigation and fertilization can benefit producers through increased production and carbon sequestration. However, a restriction in these practices can also cause changes within the plant and soil communities. One-way agricultural land might be suddenly restricted from irrigation and fertilization is through abandonment. Abandonment of agricultural land refers to when previously managed and harvested land ceases to be used for crop production and is excluded from all management practices (MacDonald et al. 2000). This could be a result of numerous situations, including farm closure, lack of productivity, or a change in management practices (MacDonald et al. 2000). Abandoning agricultural land represents a major change in land management. Such changes have been shown to decrease productivity while facilitating the invasion of woody or weedy species, ultimately declining overall ecosystem function (Lopez-Toledo and Martinez-Ramos 2011). The effects of abandoning a piece of agricultural land will greatly vary depending on previous land management history, type of abandonment, and environmental conditions (MacDonald et al. 2000).

Previous studies on the effects agricultural abandonment have shown varying results regarding plant diversity, plant productivity, and soil carbon. A study performed by Marriott et al. (2009) found that agricultural abandonment resulted in a shift in plant community composition, increased species richness, and decreased productivity. These changes were thought to be heavily influenced by the cessation of fertilizer application, allowing for less competitive species to grow, while also reducing soil fertility. Lie et al. (2020) observed as abandoned cropland moved back towards native vegetation in southwest China. Larger shrub and forb species began to grow and contribute to biomass volume and organic matter input, influencing increases in plant biomass and soil organic carbon concentrations in the abandoned cropland. A review study conducted in 2016 by Deng et al. looked at changes in soil carbon stocks after land-use changes, considering 103 previous experiments. On average, they found land-use changes, including abandonment, resulted in decreased soil carbon stocks. While the results of these studies vary, a common agreement is that climatic factors and pre-existing conditions can hugely influence how land responds to abandonment (When et al. 2017, Deng et al. 2016, Marriott et al. 2009).

Climatic factors, including mean annual temperature and mean annual precipitation, impact the fate of abandoned agricultural land (Deng et al. 2016). Temperature and moisture are limiting factors of plant productivity and decomposition of organic matter. If abandoned farmland is restricted by a hot, dry climate, plant production and soil carbon sequestration may be lowered as a result (Deng et al. 2016). Pre-existing conditions also determine how land will respond to abandonment. Initial species composition, presence of weedy species in the seedbank, and previous management history all influence what the plant community post-abandonment will look like (Marriott et al. 2009). From these previous findings, it appears that the factors with the greatest impact on abandoned agricultural land are pre-existing environmental conditions.

As climate is such an important factor in determining how land will respond to abandonment (Deng et al. 2016), results from different climatic regions should not be compared. Of the 103 studies discussed in Deng et al.’s (2016) review paper, only one of these studies was performed in Canada. This represents a vast literature gap when considering abandoned agricultural land in climates throughout Canada, including within B.C. Agricultural land covers 5% of B.C.’s land mass (Provincial Agricultural Land Commission 2014). This percentage represents many acres of land that have potential for supporting economies through productivity and mitigating climate change through carbon sequestration. Understanding how agricultural land in B.C. responds to changes in management is important for deciding upon proper management for increased productivity and sustainability.

This study explored the effects of abandonment of irrigation and fertilization. Actively irrigated, fertilized cropland was compared to cropland abandoned by these practices, contrasting 1) plant community dynamics, 2) aboveground and belowground plant productivity, 3) forage quality, and 4) soil carbon, nitrogen, and organic matter. These variables were assessed through a two-year field study conducted on a perennial cropping system.

MATERIALS & METHODS

Field Study Design

Study site

The study site for this experiment involves the same study location as mentioned in Chapter 2 (see page 13), located on an agricultural field composed of a perennial cropping system. Prior to 2004, a rectangular area of land was continuously irrigated and annually fertilized. In 2004, a centre pivot sprinkler system replaced the laterally moving sprinkler system, cutting off a portion of the field from irrigation. This cut-off portion of cropland was originally seeded with the same perennial forage blend mentioned in Chapter 2 (see page 13, Table 2.1) but is no longer irrigated, fertilized, or used for crop production, representing abandoned cropland. A study enclosure was constructed on this abandoned area, measuring approximately 20 m x 30 m, and was organized using the same study design as Chapter 2 (Figure 3.1). A detailed map of the study site and design are displayed in Appendix D. Plant and soil characteristics were compared between this abandoned enclosure and the continuously irrigated, annually fertilized enclosure described in Chapter 2 (see pp. 18-22). Field data were collected from both enclosures throughout 2020 and 2021.

Figure 3.1: Completed experimental set-up on abandoned cropland in May 2020.

Site monitoring

Site monitoring within the study enclosures occurred throughout each study year. Site monitoring involved collecting soil moisture data, mowing between plots, and taking photopoints following the same methods detailed in Chapter 2 (see page 16).

Weather data

Weather data of the study enclosure was collected using the same HOBO weather station mentioned in Chapter 2 (see page 16). Temperature and precipitation data were collected from May to October 2020 and April to September 2021.

Data Collection and Analysis

Sample collection and analysis

Throughout 2020 and 2021 growing seasons, field data was collected on plant community diversity and composition, aboveground and belowground plant productivity, forage quality, and soil carbon, nitrogen, and organic matter. All sample and data collection followed the same protocols outlined in Chapter 2. See pages 18 -22 for a detailed explanation of sampling protocols.

Statistical analyses

Analyses were made to compare plant and soil characteristics between active and abandoned enclosures. To ensure that mowing treatment was not a confound, comparisons for this chapter were only made between study plots for which mowing treatments would not differ. Height measurements, root biomass, Shannon and Simpson diversity, species richness, and species composition were compared between control plots throughout the duration of the study. Aboveground biomass was compared between enclosures at a mowing height of 0 cm in June 2020, before mowing treatments had been implemented, and within control plots in August 2021 at the time of final harvest.

All statistical analyses and figures were produced using R for Statistical Computing, version 1.4.1103 “Wax Begonia” (R Core Team 2021). In all cases, significance was defined by $p < 0.05$. Plant diversity, productivity, forage quality, and soil characteristic responses were compared between enclosures using mixed effect models from the “lme4” package. All models included block as a random value. Tukey’s HSD post hoc analyses were performed on all models using the “emmeans” package.

RESULTS

Weather, irrigation, and soil moisture data

Temperature, precipitation, and irrigation data recorded throughout the study duration are provided in Chapter 2 (see page 25, Figure 2.7). Soil moisture data was recorded throughout both study enclosures from May to August of 2020 and 2021 (Figure 3.2). In both years, the abandoned enclosure was lower in volumetric water content (VWC) throughout the growing season than the active enclosure. In 2021 (Figure 3.2B), the abandoned enclosure was extremely low in soil moisture, with average values lower than 10 % VWC throughout the entire season.

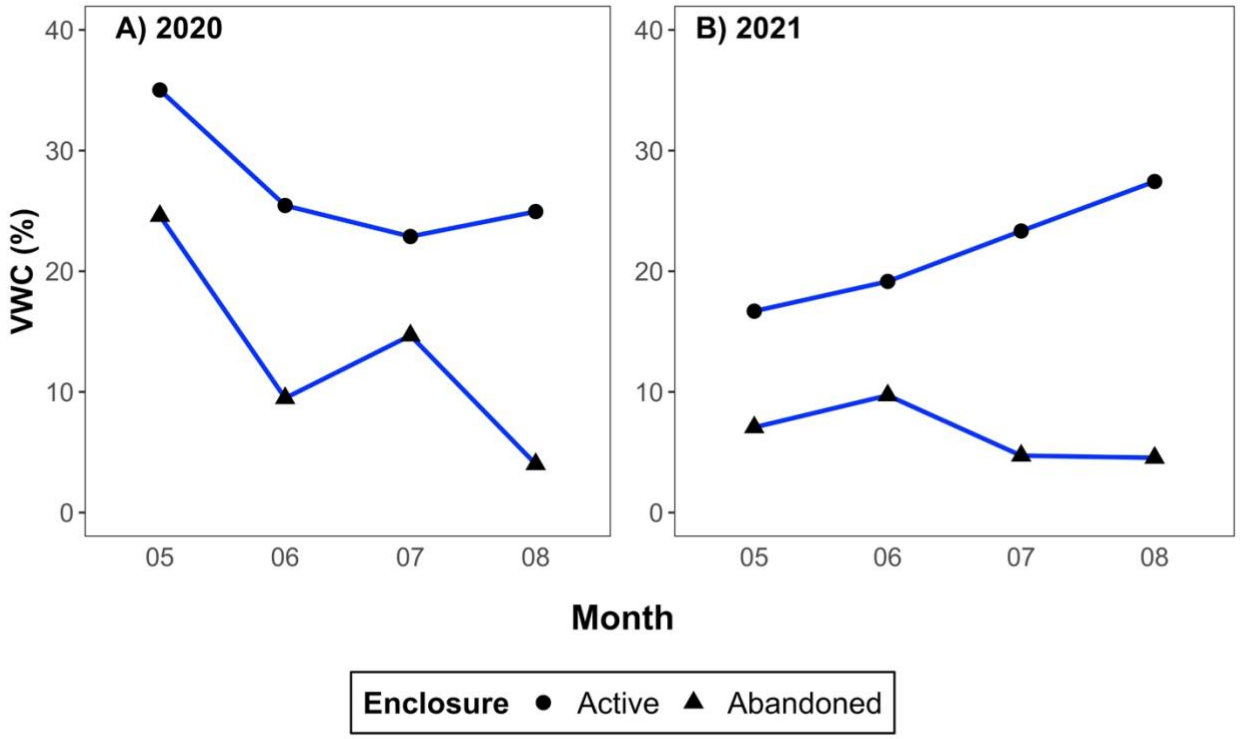

Figure 3.2: Average monthly soil moisture represented as volumetric water content (VWC) within study enclosures throughout the growing season of A) 2020, and B) 2021.

Plant community diversity and composition

Measures of plant diversity were compared between control plots of active and abandoned enclosures in June 2020 and August 2021 (Figure 3.3). For all examined measures of diversity (Shannon-Weiner diversity index and species richness), at both survey events, the active enclosure was shown to have significantly higher plant diversity than the abandoned enclosure. See Table 3.1 for a list of comparisons and corresponding p-values. When comparing across sampling events in Figure 3.3, active cropland plots did not differ in their levels of diversity from June 2020 to August 2021. Abandoned study plots, however, showed lower values for both measures of diversity in August 2021 compared to June 2020.

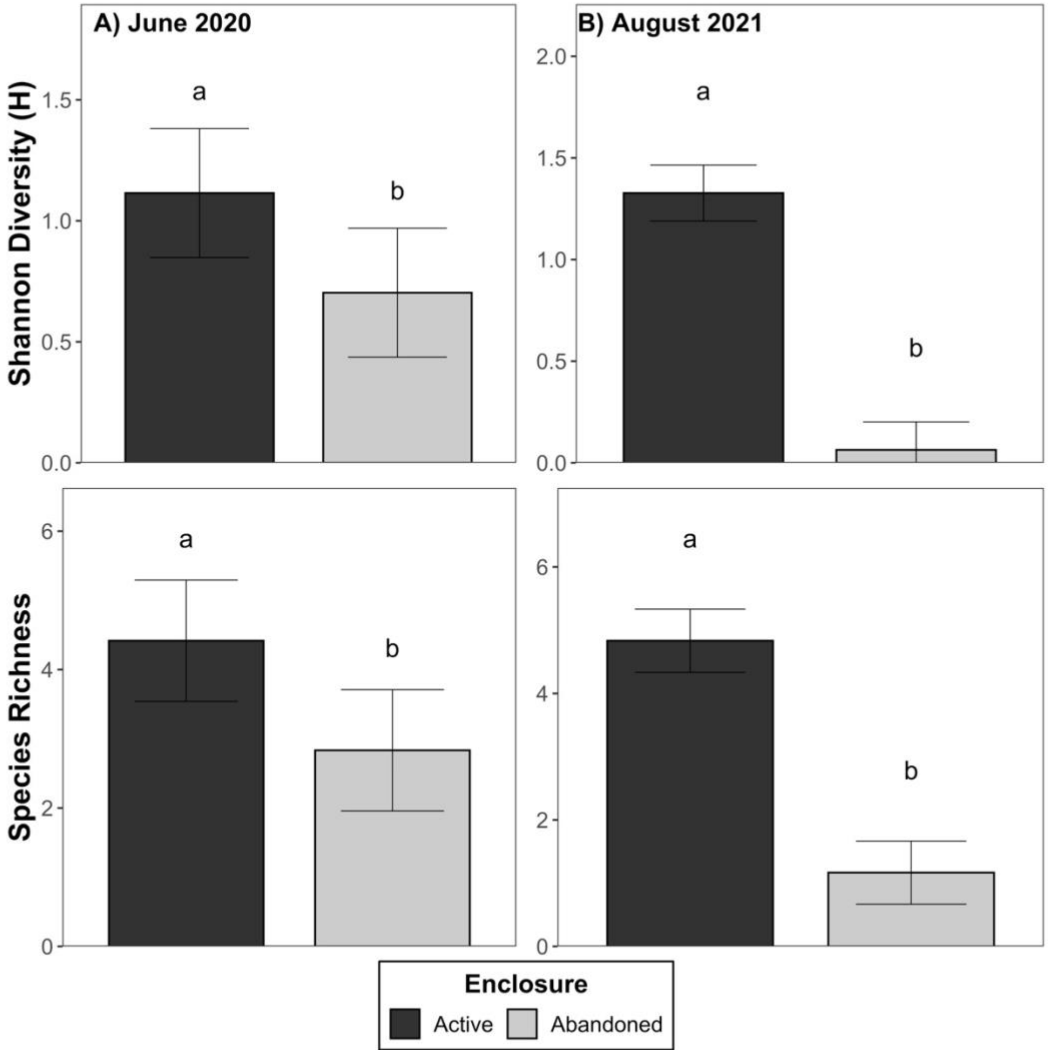

Figure 3.3: Values of Shannon-Weiner diversity and species richness within control plots of both active and abandoned enclosures in A) June 2020; and B) August 2021, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Table 3.1: Summary table of plant diversity comparisons between active and abandoned enclosures made in Figure 3.3 showing F-value from ANOVA and p-value from Tukey HSD post-hoc analyses.

Index and Timing	**F-Value**	**p-value**
Shannon Diversity – June 2020	12.87	0.023
Shannon Diversity – August 2021	525	<0.0001
Species Richness – June 2020	29.36	<0.0001
Species Richness – August 2021	187	<0.0001

Species composition of the two study enclosures throughout the study's duration is shown in Figure 3.4. The compositions of the two enclosures were shown to be much different. The active enclosure was composed mostly of the seeded forage species; *P. pratense*, *T. pratense* and *M. sativa*, along with some cover of *Taraxacum offiniale, Lolium perenne*, and *Poa pratensis*. The abandoned enclosure lacked cover of seeded forage species and was composed of Crepis spp. and *P. pratensis*. In August 2021, the abandoned enclosure was dominated by *P. pratensis*, with an average absolute cover of 67.92 %.

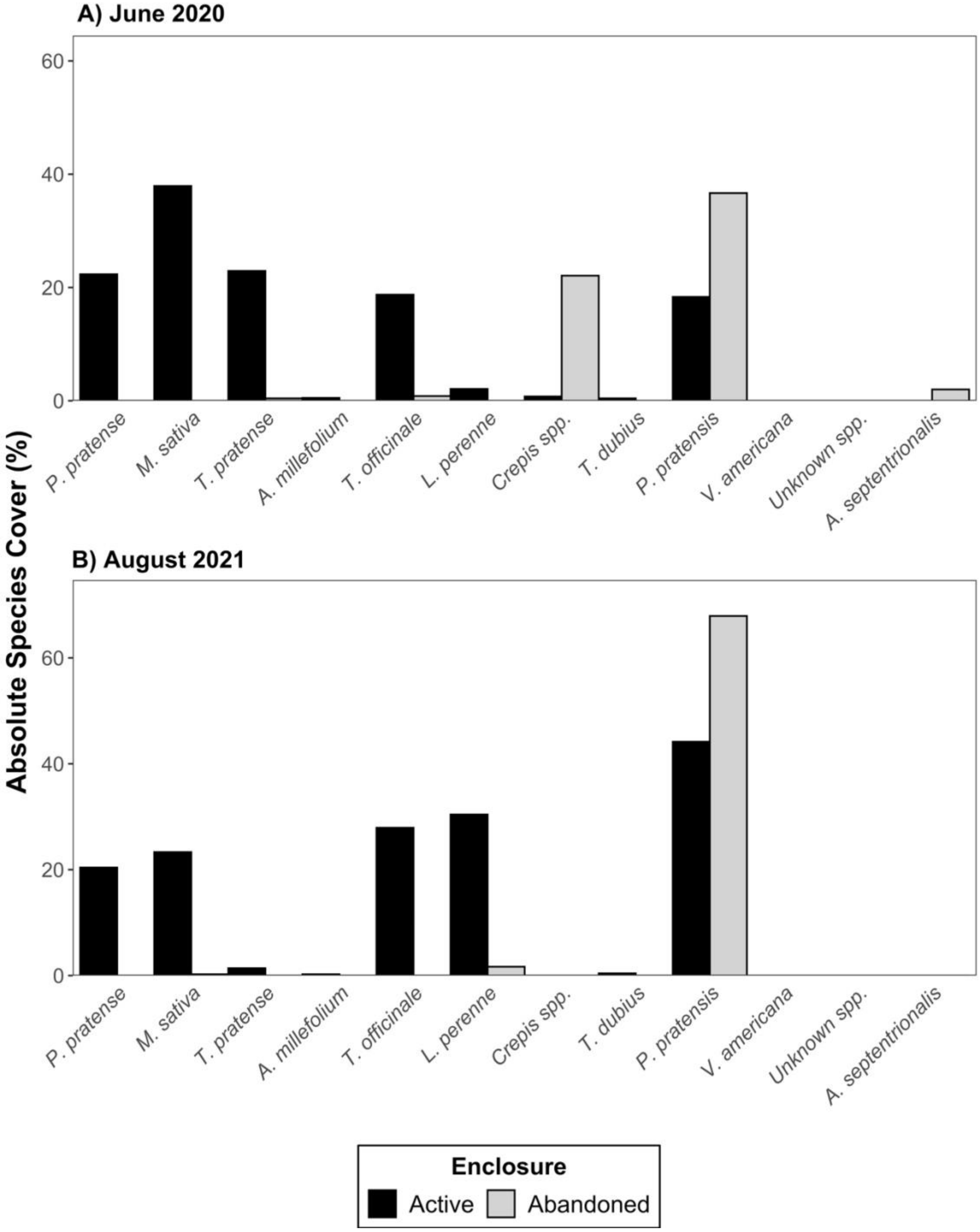

Figure 3.4: Absolute percent cover of species recorded in active and abandoned control plots at A) June 2020 and B) August 2021 survey dates (n=12).

Photos of control plots at the time of surveys in are shown Figures 3.5 and 3.6, showing species composition and plant productivity. In June 2020 (Figure 3.5A), the active cropland control plot was notably green and productive, with the seeded species composing the majority of plant cover. The control plot within the abandoned enclosure at this survey date (Figure 3.5B) was dominated by Crepis spp. and *P. pratensis,* and while less productive than the active plot, was visually green and the plants appeared to be healthy. In August 2021, the active enclosure control plot (Figure 3.6A) was again composed mainly of seeded forage species, along with some standing litter. The abandoned control plot (Figure 3.6B) was comprised mainly of standing and ground litter. Standing litter was recorded as cover of *P. pratensis*.

Figure 3.5: Control plots in June 2020 showing community composition and productivity in the A) active cropland enclosure; and B) abandoned cropland enclosure.

Figure 3.6: Control plots in August 2021 showing community composition and productivity in the A) active cropland enclosure; and B) abandoned cropland enclosure.

Aboveground plant productivity

The study enclosures showed significant differences in biomass production throughout the duration of the study. In June 2020 (Figure 3.7A), biomass was harvested within M0 plots in both enclosures. Active cropland plots produced significantly higher biomass than abandoned plots (F = 209.1, $p < 0.0001$). In August 2021 (Figure 3.7B), biomass was harvested within control plots in both enclosures, active plots again saw significantly higher values of biomass production (F = 101, $p < 0.0001$).

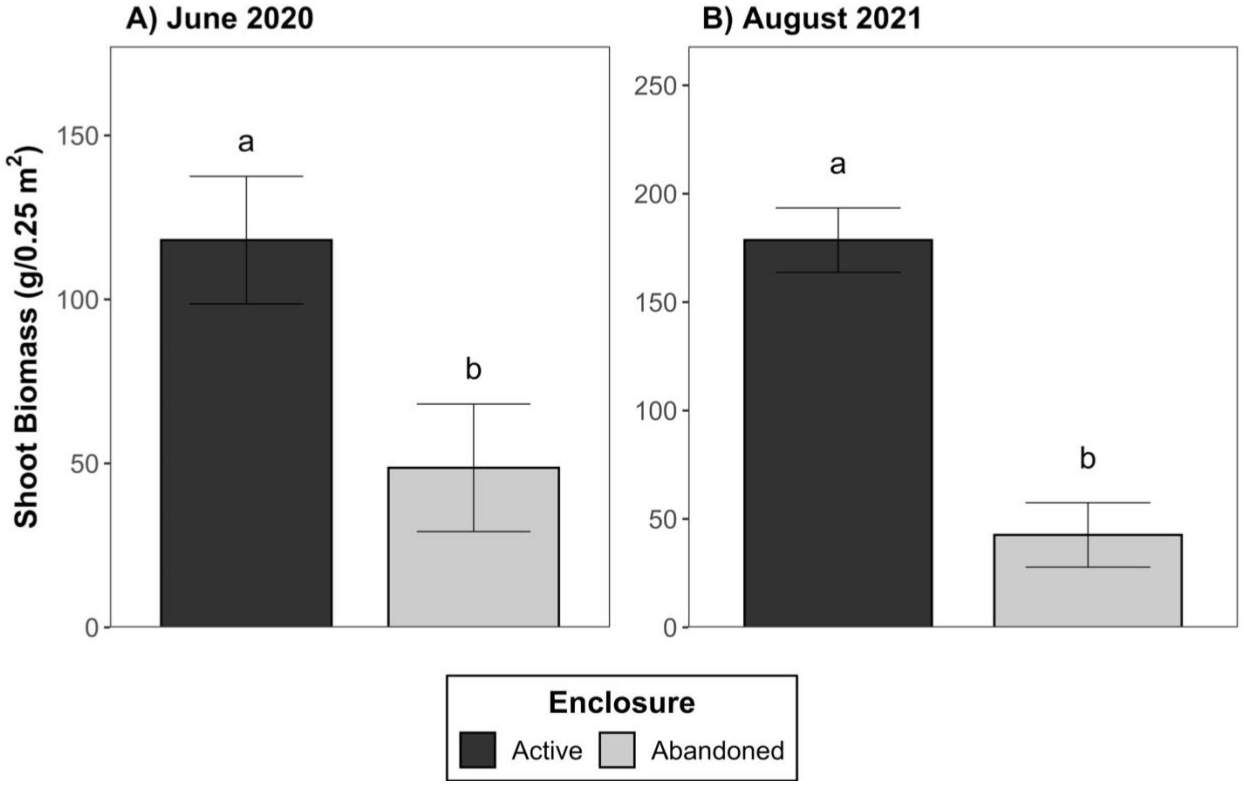

Figure 3.7: Biomass collected at a height of 0 cm within active and abandoned study enclosures in A) June 2020 within M0 plots and B) August 2021 within control plots, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, n=12).

Height measurements and two-month regrowth response

To assess response to defoliation, height measurements were taken before and after biomass collection and the two-month regrowth response was assessed. Throughout 2020 (Figure 3.8) and 2021 (Figure 3.9) the active study plots consistently showed significantly higher shoot height values and regrowth responses than abandoned study plots. See Table 3.2 for a list of comparisons and corresponding p-values. In 2021, the regrowth response to defoliation seen within abandoned plots was notably lower than it was in 2020.

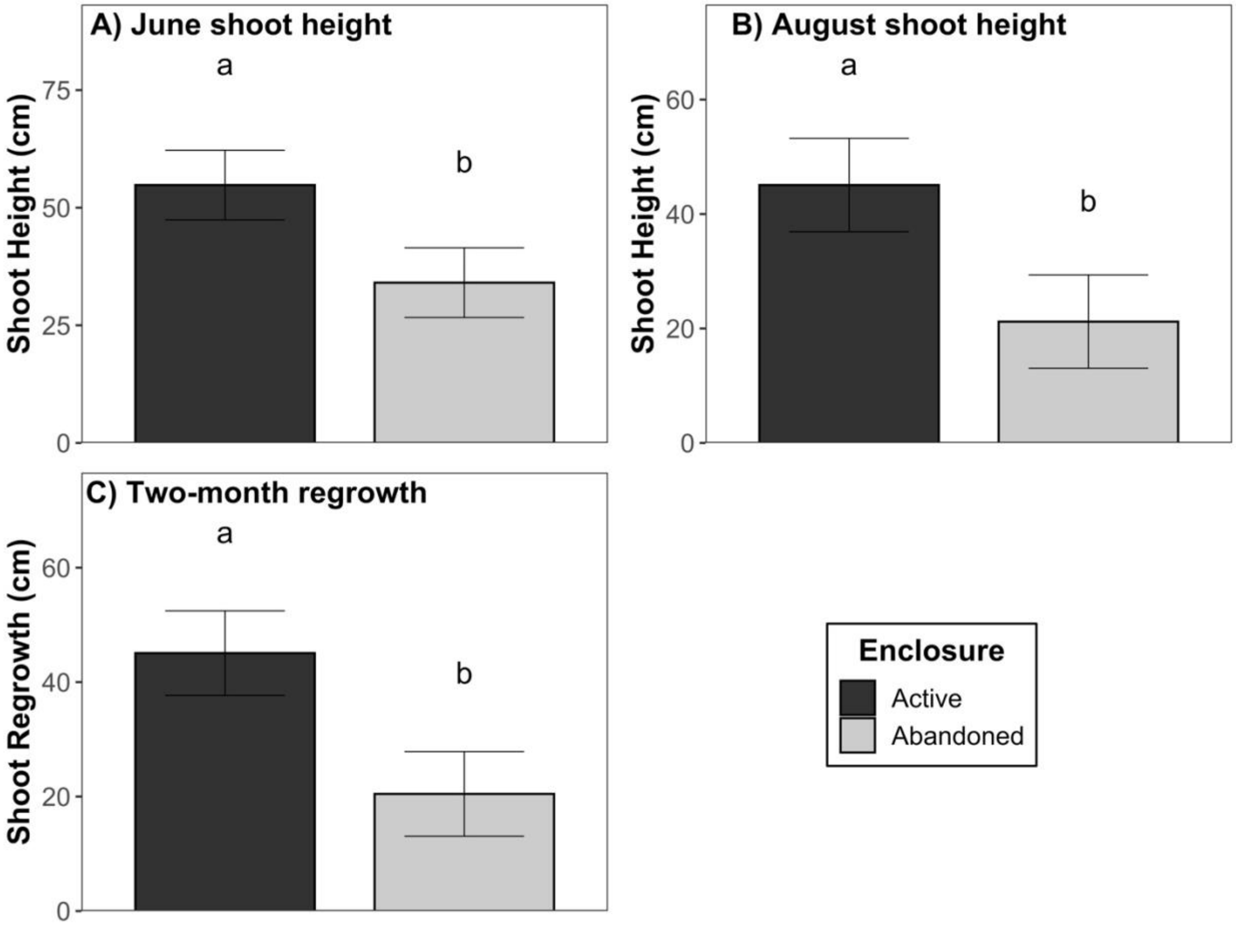

Figure 3.8: Aboveground productivity across within M0 plots predicted by plant height: A) Shoot height in June 2020, prior to collection of biomass; B) Shoot height in August 2020, two months after biomass collection; C) Amount of regrowth after June 2020 biomass collection, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

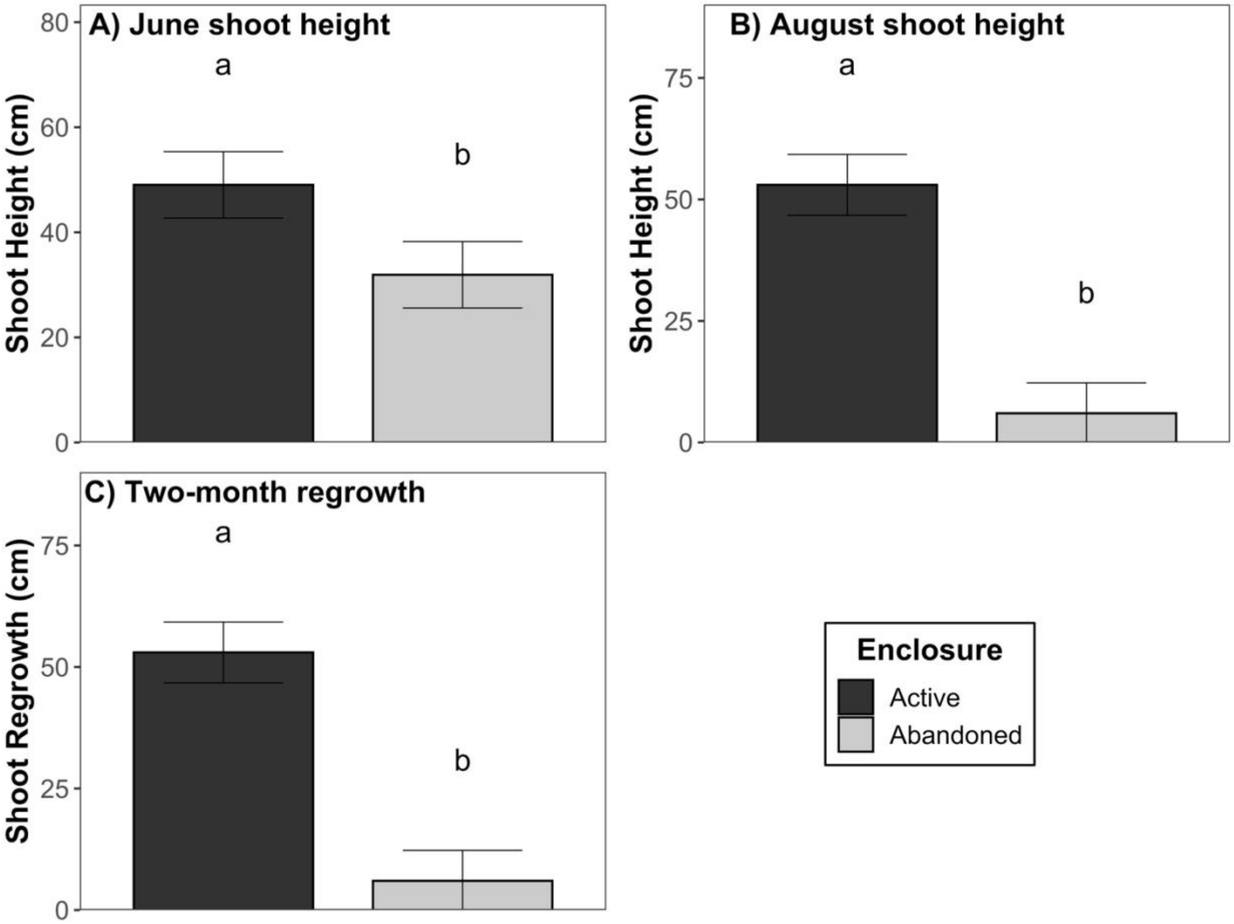

Figure 3.9: Aboveground productivity across within M0 plots predicted by plant height: A) Shoot height in June 2021, prior to collection of biomass; B) Shoot height in August 2021, two months after biomass collection; C) Amount of regrowth in August, two months after June biomass collection, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Table 3.2: Summary table of plant height and regrowth comparisons between active and abandoned enclosures made in Figure 3.8 and 3.9 showing F-value from ANOVA and p-value from Tukey HSD post-hoc analyses.

Variable and Timing	**F-Value**	**p-value**
Shoot height – June 2020	69.17	<0.0001
Shoot height – August 2020	141.2	<0.0001
Shoot Regrowth – August 2020	125.9	<0.0001
Shoot height – June 2021	90.53	<0.0001
Shoot height – August 2021	237.8	<0.0001
Shoot Regrowth – August 2021	237.8	<0.0001

Belowground plant productivity

Belowground plant productivity, estimated by root biomass volume, was shown to be significantly different between enclosures (Figure 3.10). In September 2020 (Figure 3.10A), active enclosure control plots had significantly higher levels of belowground productivity than control plots within the abandoned enclosure (F = 26.2, p = 0.0001). Similar results of belowground productivity were also seen in August 2021 (F = 11.01, p = 0.0041: Figure 3.10B).

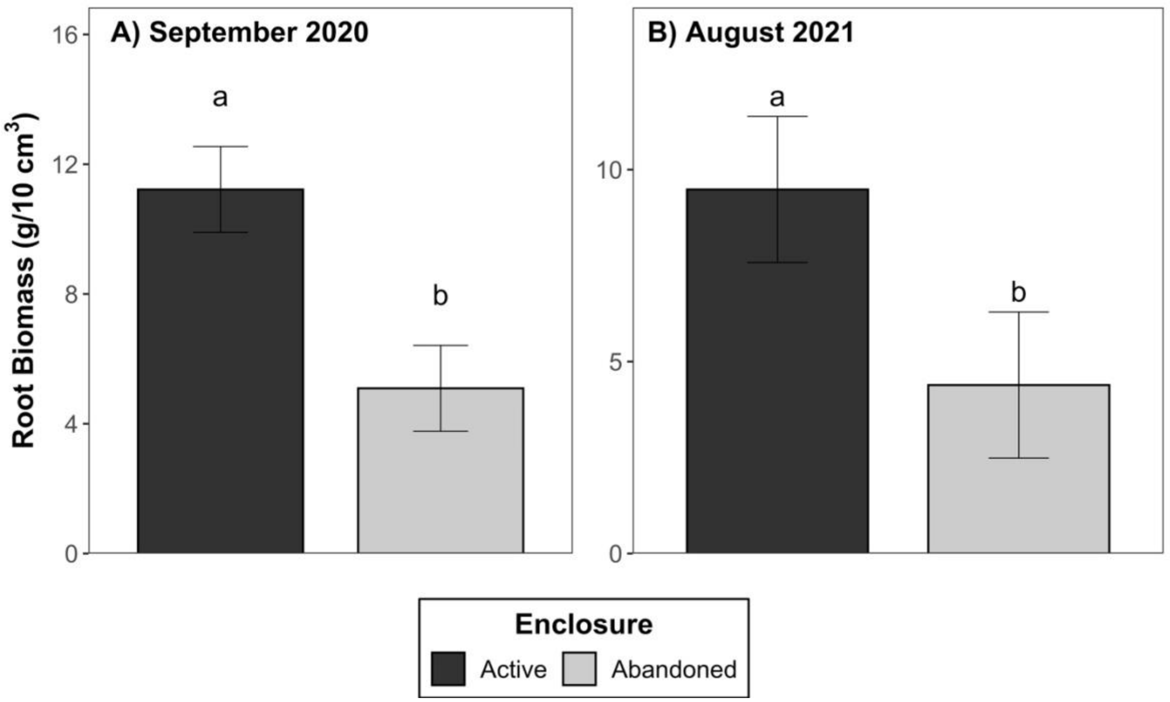

Figure 3.10: Root biomass collected within control plots throughout active and abandoned enclosures in A) September 2020 and B) August 2021, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

Forage quality

Forage quality was compared between samples collected within active and abandoned enclosures within M0 treatments plots in June 2020 (Figure 3.11). Samples taken from active cropland plots were shown to have significantly higher values of crude protein ($F = 94.17$, $p = <0.0001$), soluble protein ($F = 65.78$, $p = <0.0001$) and TDN ($F = 9.087$, $p = 0.0078$), and were significantly lower in ADF ($F = 36.54$, $p = <0.0001$) and lignin ($F = 18.72$, $p = 0.0005$) than samples taken from abandoned cropland plots.

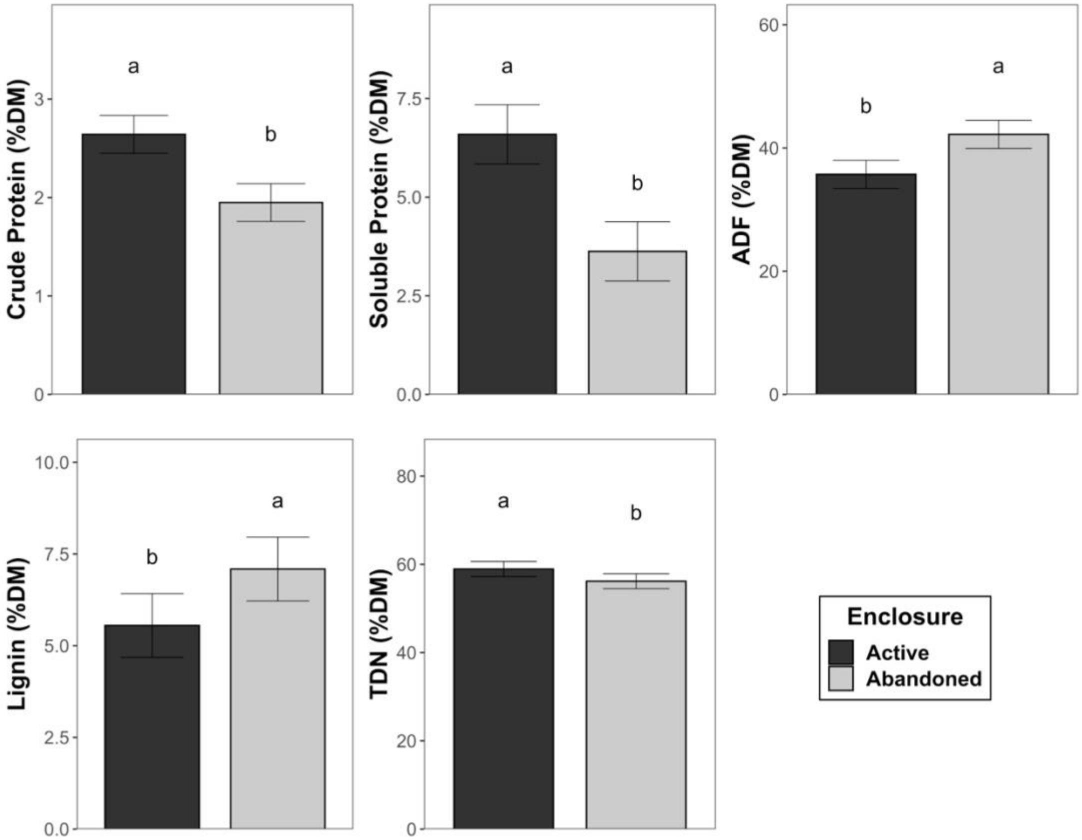

Figure 3.11: Forage analysis of biomass samples harvested at 0 cm in June 2020 within both active and abandoned enclosures, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA (p<0.05, n=12).

Soil carbon, nitrogen, and organic matter

Soils collected within control plots in August 2021 were analyzed for levels of total carbon, total nitrogen, and soil organic matter and compared between active and abandoned control plots (Figure 3.12). Plots within the active enclosure were shown to have significantly higher levels of total carbon (F = 6.303, p = 0.0179: Figure 3.12A), total nitrogen (F = 11.45, p = 0.0021: Figure 3.12B), and soil organic matter (F = 35.15, p = <0.0001: Figure 3.12C) than plots within the abandoned enclosure.

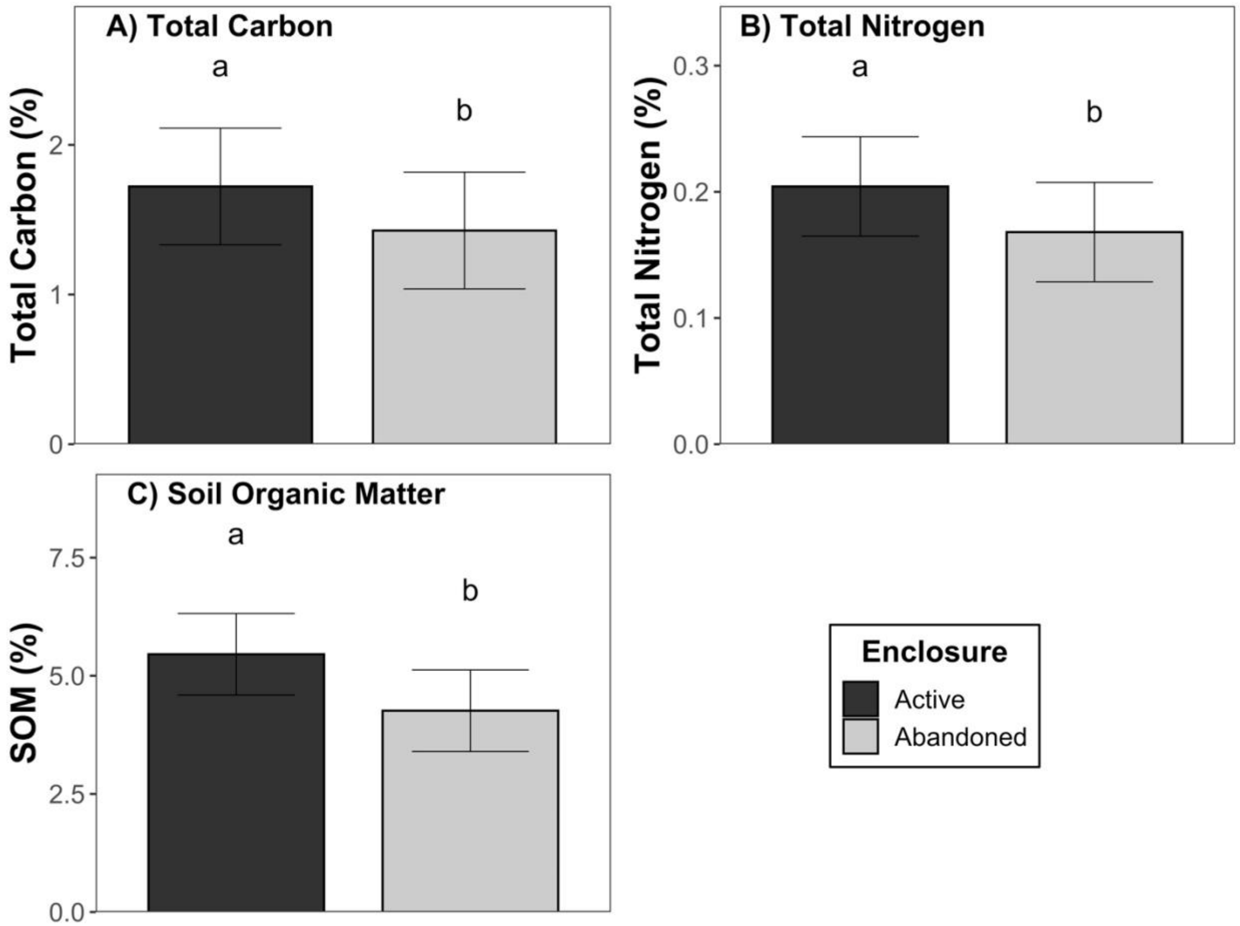

Figure 3.12: Comparison of soil metrics between study enclosures collected in August 2021 within control plots at a depth of 0 to 15 cm; A) Total Carbon; B) Total Nitrogen; and C) Soil Organic Matter, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$, $n=12$).

DISCUSSION

Plant community diversity and composition

Plant species diversity can be altered by different land management styles (Müller et al. 2016), an affect seen in this study. Actively irrigated and fertilized cropland saw higher levels of plant diversity than abandoned cropland throughout the duration of the study. These differences in plant diversity were linked to differences in plant community composition seen throughout the two study enclosures. The active cropland had a high cover of seeded forage species, along with several native and weedy species that had become incorporated into the field over time. The abandoned cropland was lacking cover of forage species and was dominated by cover of *Crepis* spp. and *P.*

pratensis, both which are categorized as invasive species within B.C. (Klinkenberg 2020, Invasive Terrestrial Plants 2021). This represented an unfavourable community change resulting from the abandonment of agricultural cropland.

The seeded forage species (*P. pratense*, *T. pratense*, and *M. sativa*) all perform better in areas that are sufficient in moisture and nutrient availability (St. John and Ogle 2008, Ogle et al. 2011, Undersander et al. 2011). When irrigation and fertilization were removed from management in 2004, water and nutrient limitations were introduced to the forage species in the abandoned area. This change in management likely caused a reduction in the success of seeded forage species, reducing competition and enabling the growth of other less-dominant species (Yang et al. 2020). *P. pratensis* was already established on the cropland prior to abandonment, as it was seen within the plant community of currently active cropland. The decrease in cover of the three forage species facilitated the increase in cover of *P. pratensis,* as this species is known to invade and exploit areas that no longer support the growth of previously dominant species (Bork et al. 2008). This effect was further seen in 2021 within the abandoned enclosure as dry conditions could not support the growth of Crepis spp. or *A. septentrionalis*, species seen in 2020, resulting in further increases in *P. pratensis* cover and lower measures of species diversity.

Traditional agricultural goals manage land for productivity rather than diversity. Irrigation and fertilization are both commonly used to achieve increased plant productivity but can also affect plant diversity (Müller et al. 2016). At the study site, the coupled use of irrigation and fertilization on active cropland was maintaining biodiversity, allowing the successful growth of *P. pratense, T. pratense,* and *M. sativa*, along with numerous unseeded species. When managing a perennial cropping system in dry climatic conditions, moving away from irrigation and fertilization has been shown to result in unfavourable plant community changes, causing the failure of seeded forage species, increases in invasive species cover, and overall reductions in biodiversity.

Aboveground plant productivity

Irrigation and fertilization are used in agricultural operations to increase plant productivity (Conant et al. 2001). Abandonment of these techniques could be expected to decrease the productivity of agricultural land, which was seen at the study site. Aboveground plant productivity, characterized by photopoints, biomass samples, and height measurements, was significantly lower for abandoned cropland than for active cropland. This difference in productivity can be attributed to the climatic characteristics of the study area and the water and nutrient requirements of the seeded forage species.

Reductions in yields of forage crops are frequently related to water limitations and hot temperatures (Undersander et al. 2011; Bittman et al. 1999). The Chilcotin region of B.C., is characterized by hot, dry summers (Cariboo-Chilcotin Coast – Overview 2021), conditions that were shown by the temperature and precipitation data gathered throughout the duration of this study. Without supplemental irrigation, soil moisture values remained low throughout the growing season, forage species were too restricted by water limitations, and productivity was severely decreased. Water and nutrient availability can also influence levels of compensatory growth in response to defoliation (Zhao et al. 2008). This effect was shown within the abandoned cropland which produced much lower regrowth after mowing compared to active cropland. The combination of intense defoliation, which was used to collect the biomass samples, and severe drought caused plants within abandoned cropland to exhibit decreased growth (Zhao et al. 2008).

The importance of irrigation was reinforced when looking at the productivity of abandoned cropland in 2021, throughout which there was virtually no rainfall during the growing season. Productivity was further reduced in this study year, with photopoints showing the plant community to be composed majorly of standing litter as *P. pratensis* plants went dormant due to moisture limitations (Cook n.d.). From the measures of aboveground plant productivity observed in this study, it appeared as though irrigation and fertilization were necessary in hot, dry regions such as the Chilcotin in order to produce high yielding forage crops that are resilient to harvest.

Belowground productivity

Levels of belowground productivity were reduced by abandonment of irrigation and fertilization practices. This change mirrored the reductions seen in aboveground productivity which occurred when forage species become water and nutrient restricted (Undersander et al. 2011; Bittman et al.

1999). The difference in levels of root biomass between enclosures was also partly due to species composition. Legume species present throughout active cropland, *T. pratense* and *M. sativa*, contain large tap roots which made up more biomass than the rhizomatous root systems of *P. pratensis* throughout the abandoned cropland (Bork et al 2018; Clark 2004). Utilizing irrigation and fertilization promoted belowground production, contributing to the carbon pool of agricultural land (Ziter and Macdougall 2013).

Forage quality

Abandonment of irrigation and fertilization had significant effects on forage quality. The biomass samples collected within the actively irrigated and fertilized enclosure were of much higher forage quality than those collected within abandoned cropland. This reduction in forage quality seen in abandoned pasture was greatly due to the difference in species composition and productivity seen across these two enclosures. The forage species occupying the active cropland are all known for their high composition of fibre and nutrients and level of palatability (St. John and Ogle 2008; Ogle et al. 2011; Undersander et al. 2011). *P. pratensis*, while still a palatable grass, does not contain enough nutrient value to compare to that of *P. pratense*, *T. pratense*, and *M. sativa*. The palatability and nutritive value of *P. pratensis* is substantially decreased when plants go dormant during hot, dry conditions (Cassida and Kaatz 2019), resulting in a further reduction of forage quality within the abandoned enclosure. Using irrigation and fertilization to manage cropland maintained the presence and productivity of desired forage species, which encouraged the production of high-quality forage.

Soil carbon, nitrogen, and organic matter

Changes in management affect levels of soil nutrients, ultimately causing changes in carbon storage (Conant et al. 2003). The abandoned enclosure saw lower levels of soil carbon, nitrogen, and organic matter than actively irrigated cropland. Differences in these soil variables can be attributed to the lower productivity and species composition of the abandoned enclosure. Levels of soil carbon strongly correlate with plant productivity (Kunkel et al. 2011). The reductions in aboveground and belowground productivity seen in the absence of irrigation and fertilization were responsible for the decreased levels of soil carbon and organic matter within the abandoned enclosure. Lowered levels of nitrogen were likely due to the lack of annual synthetic fertilizer application and absence of nitrogen-fixing plants. *T. pratense* and *M. sativa* are both nitrogen-fixing species which provide nitrogen required for plant growth (St. John and Ogle 2008, Undersander et al. 2011). Without nitrogen-fixing species and the supplemental nitrogen provided through fertilization, the soil nitrogen of abandoned cropland was lower than areas where these two sources of nitrogen are available.

In this study, abandonment of irrigation and fertilization negatively impacted the soil community and caused carbon losses. Continued application of these practices can increase soil quality and carbon sequestration, helping operations remain productive while offsetting some of their greenhouse gas emissions.

CONCLUSION

It is well known, both throughout scientific literature and agricultural practices, that irrigation and fertilization enhance plant productivity, especially in regions with hot, dry climates. What is less known is how agricultural land responds when it is abandoned by these practices. The transition of land from an actively irrigated and fertilized system to abandoned cropland represented a major management change. This change was seen to negatively impact all studied aspects of plant and soil communities. Without irrigation and fertilization, forage species were unable to be maintained within the plant community, which increased potential for invasion. As forage species dwindled and were replaced by cover of *P. pratensis*, decreases were seen in plant diversity, aboveground and belowground plant productivity, forage quality, and soil carbon, nitrogen, and organic matter, and ultimately caused decreases in the carbon storage of the landscape. The results of this study provide support for the practices of irrigation and fertilization to enhance productivity and carbon storage, producing agricultural systems that favour rates of carbon sequestration. However, this study has also revealed that agricultural abandonment was an unfavourable land management change. Water shortages and the high cost of synthetic fertilizer are current concerns for the agriculture industry of B.C., both of which could lead to the abandonment of irrigation and fertilization from cropping systems throughout the province. As the negative impacts of such abandonment have been shown, further research must determine how landscapes can transition from active to non-irrigated, unfertilized cropland without experiencing the reductions in productivity and carbon sequestration seen in this study. This will likely incorporate interventions to move the cropping system away from forage species with high nutrient and moisture requirements to a plant community that is better suited to the natural environment, avoiding invasion of unwanted species which threaten biodiversity, productivity, and carbon storage.

LITERATURE CITED

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Chapter 4 - RESEARCH CONCLUSIONS, MANAGEMENT IMPLICATIONS, AND FUTURE RESEARCH

RESEARCH CONCLUSIONS

The production of forage crops throughout British Columbia is an important industry that provides social, economic, and environmental benefits to the province and its citizens (Ference & Company Consulting Ltd 2016). As the effects of climate change become more prominent, and the human population continues to grow, forage productions will need to adjust practices to both adapt to and mitigate changing environmental conditions while increasing crop production (Howden et al. 2007). Agricultural management techniques have potential to achieve this goal through increased plant productivity and contributions to carbon sequestration (Conant et al. 2001). This study examined three commonly used management techniques that have been shown to affect plant productivity and soil properties of agricultural land: mowing, irrigation, and fertilization. The specific objectives of this experiment were to 1) investigate the effects of mowing height on forage production and soil characteristics; and 2) to examine plant and soil responses to abandonment of irrigation and fertilization. These objectives were assessed through a two-year field study conducted on a perennial cropping system near Alexis Creek, B.C.

Key findings of field study

- **Mowing height caused variable effects on forage species composition, plant productivity, forage quality, and soil characteristics of perennial cropping systems**

  Previous studies have shown that mowing is capable of altering plant diversity and productivity and forage quality depending on intensity (Yang et al. 2020; Wiersma et al. 2007). Changes in productivity have been shown to correlate with levels of soil carbon (Kunkel et al. 2011; Conant et al. 2001), causing increases in carbon sequestration of productive agricultural land (Donovan 2013; Conant et al. 2001). This study showed that in all cases, mowing stimulated compensatory growth and increased plant productivity compared to that of unmowed areas. There appeared to be a trade-off between productivity and forage quality. Mowing at a low cutting height increased productivity but lowered forage quality. High cutting heights produced lower levels of productivity, but higher quality forage. Low cutting heights promoted increases in *M. sativa* cover, and reduced *P. pratense* cover. This coincided with studies that have similarly examined the same forage species (Undersander et al. 2011; Wiersma et al. 2007). Of all cutting heights, the 10 cm treatment produced the highest levels of plant productivity. This high level of productivity correlated with levels of soil carbon, which were also highest for the 10 cm mowing treatment.

- **Abandonment of irrigation and fertilization within a perennial cropping system caused unfavourable plant community changes and declines in plant productivity, forage quality, and soil carbon**

Across B.C., irrigation and fertilization are used for the successful production of forage crops (Commodity 2014). These practices can impact landscapes both positively and negatively, depending on how they are managed (Arroita et al. 2013; Conant et al. 2001). As such, abandonment of these practices can also impact plant and soil characteristics of agricultural land. Response to abandonment can be variable and is dependent upon management history and environmental conditions (MacDonald et al. 2000). This study examined abandonment of irrigation and fertilization from a perennial cropping system in the interior of B.C. Overall, abandonment showed negative impacts on both plant and soil characteristics. Abandonment of irrigation and fertilization introduced severe moisture and nutrient limitations to the cropping system, making it unable to support the seeded forage species (*P. pratense, T. pratense,* and *M. sativa*). As forage species declined, the potential for invasion increased. The abandoned cropland was dominated by *P. pratensis*, and measures of diversity were drastically reduced compared to that of active cropland. Water and nutrient limitations also decreased plant productivity; this effect was exaggerated by dry conditions, which are typically seen throughout the summers of B.C.'s interior regions. The absence of forage species and low levels of productivity within abandoned cropland corresponded with low forage quality. Along with the plant community, soil nutrients were also negatively impacted by abandonment. Decreased levels of soil carbon, nitrogen, and organic matter were seen as a result of decreased plant productivity, the lack of nitrogen inputs from legume species and synthetic fertilizer, and low rates of decomposition.

MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH

Mowing

Mowing is a common practice in forage operations throughout B.C., utilized for the harvest of crop material (Commodity 2014). The necessary use of this technique, along with its ability to affect plant productivity (Wan et al. 2016; Han et al. 2014; Wang et al. 2014; Turner et al. 1993; Dyer et al. 1991), forage quality (Wiersma et al. 2007), and soil nutrients (Conant et al. 2001), make it a valuable management tool for forage producers. This study identified a 10 cm cutting height to produce highest levels of plant productivity, which correlated with increased levels of soil carbon, nitrogen, and organic matter. This information should be considered in the management of perennial cropping systems that are composed of similar forage species. As the response to mowing height can greatly vary between species (Huhta et al. 2003), an effect seen in this study between *P. pratense* and *M. sativa*, these results may not be seen in dissimilar cropping systems. Before selecting a suitable cutting height, producers must also consider the production goals of their cropping system regarding forage yield versus forage quality. High cutting heights produce lower yields of higher forage quality, while lower cutting heights yield greater amounts of forage with lower forage quality (Wiersma et al. 2007). Timing of cut can also impact forage yield and quality, depending on what stage of growth a crop is currently in (Milić et al. 2019). Producers should take this into consideration when applying mowing to best suit their forage yield and quality requirements.

Future research should continue to explore the response to mowing of other commonly cultivated forage species throughout the province. This study showed that mowing has potential to increase productivity and soil carbon. Better understanding how different cropping systems respond to this practice will provide information on how to manage forage crops for optimum levels of plant productivity and carbon sequestration. The soil response to mowing should be further examined in order to better understand long-term effects. Results from this study saw soil nutrients correlate with increased productivity caused by mowing. However, changes in soil characteristics often take longer to develop (Yang et al. 2020). Examining the long-term effects of mowing on soil characteristics will help confirm the correlation between productivity and rates of carbon sequestration, helping ensure continued increases in soil nutrients as a response to mowing.

Gaining a comprehensive understanding of crop and soil response to mowing throughout B.C. will allow agricultural land to continue producing quality forage while increasing the environmental sustainability of the agricultural industry.

Use of irrigation and fertilization

The use of irrigation is common within the interior of B.C. to reduce water limitations and produce successful forage crops (Commodity 2014). Fertilization also helps promote the growth of forage species by providing necessary nutrients that are lacking in the natural soil (Undersander et al. 2011; St. John and Ogle 2008). The irrigation and fertilization management regimes that were present on the active cropland of the study site aided in the system's response to mowing, providing the necessary nutrients for plants to exhibit a strong compensatory growth response, even at low cutting heights. In cropping systems that are more restricted by access to these resources, a different response to mowing may be seen. Future research should examine the response of mowing in cropping systems with different irrigation and fertilization regimes, throughout different climatic regions of the province. The need for irrigation depends on levels of precipitation occurring throughout the growing season, which differs between the different regions of the province (MNP LLP 2020). The ability to apply irrigation is becoming a concern for some producers throughout B.C. as water licensing and environmental impacts affect access to surface and groundwater (New Requirements for Groundwater Users 2022; Ference & Company Consulting Ltd 2016; Tam et al. 2005). Fertilization requirements also vary across the province as different soil types throughout B.C. differ in nutrient composition (MNP LLP 2020). Synthetic fertilizers are often required and can be effective, but are becoming more expensive, prompting producers to explore other fertilization options (Ference & Company Consulting Ltd 2016). Understanding how crops throughout B.C. respond to mowing under varying levels or different techniques of irrigation and fertilization will provide insight on how necessary these practices are in different areas of the province for successful forage production. This will allow producers to explore options that work best in their region in order to reduce costs to their operation while maintaining crop production.

Agricultural abandonment

The negative impacts of agricultural abandonment in this study included unfavourable plant community changes and decreases in plant productivity, forage quality, and soil nutrients. Abandonment of these practices can occur for many reasons, including the inability to maintain management techniques due to expense or limited availability of resources (MacDonald et al. 2000). As concerns regarding the ability to irrigate and fertilize cropland arise, the potential for abandonment of these techniques from agricultural land increases (Ference & Company Consulting Ltd 2016). While this study showed the negative impacts that can occur from abandonment of irrigation and fertilization, it failed to experiment with ways to avoid them. Further research should explore how cropland can transition from active to abandoned without experiencing the negative impacts seen in this study. This may include introducing species that are better suited to abandoned conditions. Establishment of these species could help to replace previously dominant forage species and act to avoid invasion by weedy species that may be present in the seed bank (Marriott et al. 2009). Response to abandonment will vary with climatic conditions (Deng et al. 2016), making it important to understand impacts of abandonment throughout all regions of the province. The potential for abandonment to cause decreases in plant productivity, ultimately resulting in carbon losses (Deng et al. 2016), make it essential to understand how to avoid such impacts when changing the management of agricultural land throughout B.C.

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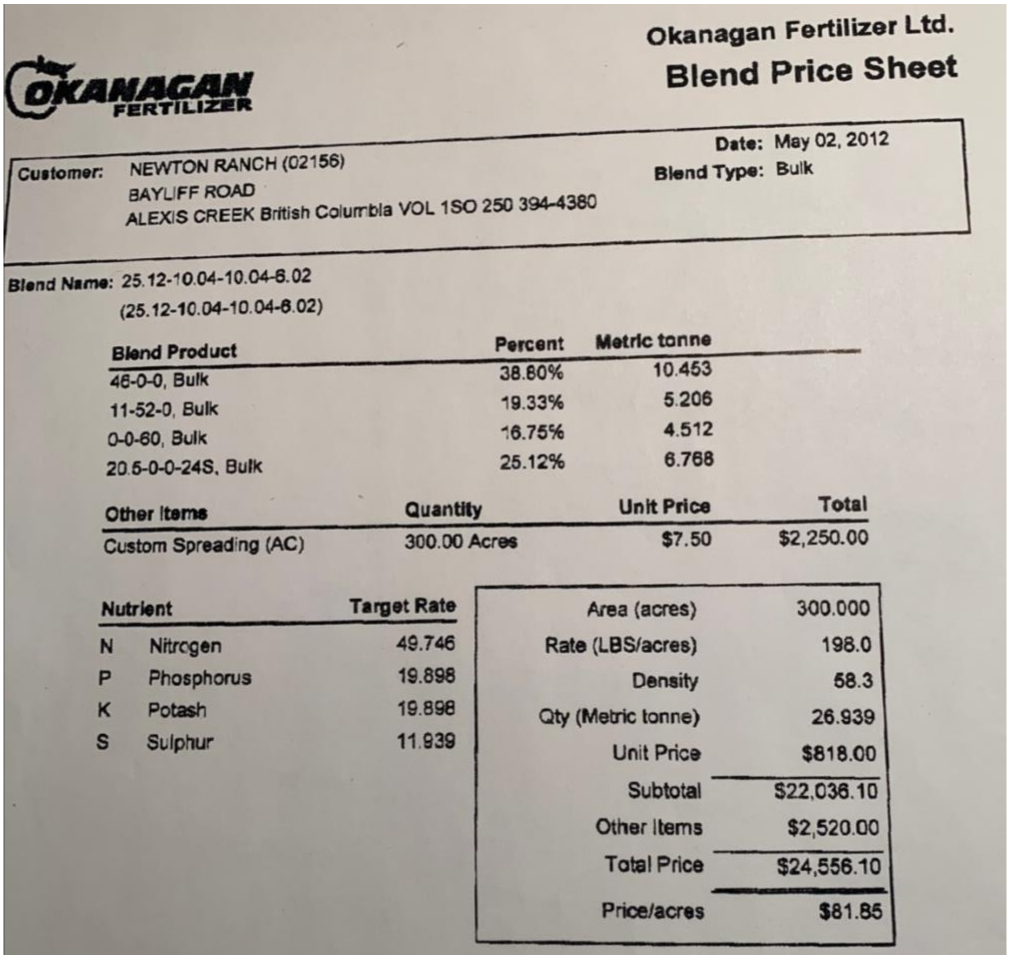
Appendix A



OKANAGAN FERTILIZER

Okanagan Fertilizer Ltd.

Blend Price Sheet

Customer: NEWTON RANCH (02156)
BAYLIFF ROAD
ALEXIS CREEK British Columbia VOL 1SO 250 394-4380

Date: May 02, 2012
Blend Type: Bulk

Blend Name: 25.12-10.04-10.04-6.02
(25.12-10.04-10.04-6.02)

Blend Product	Percent	Metric tonne
46-0-0, Bulk	38.60%	10.453
11-52-0, Bulk	19.33%	5.206
0-0-60, Bulk	16.75%	4.512
20.5-0-0-24S, Bulk	25.12%	6.768

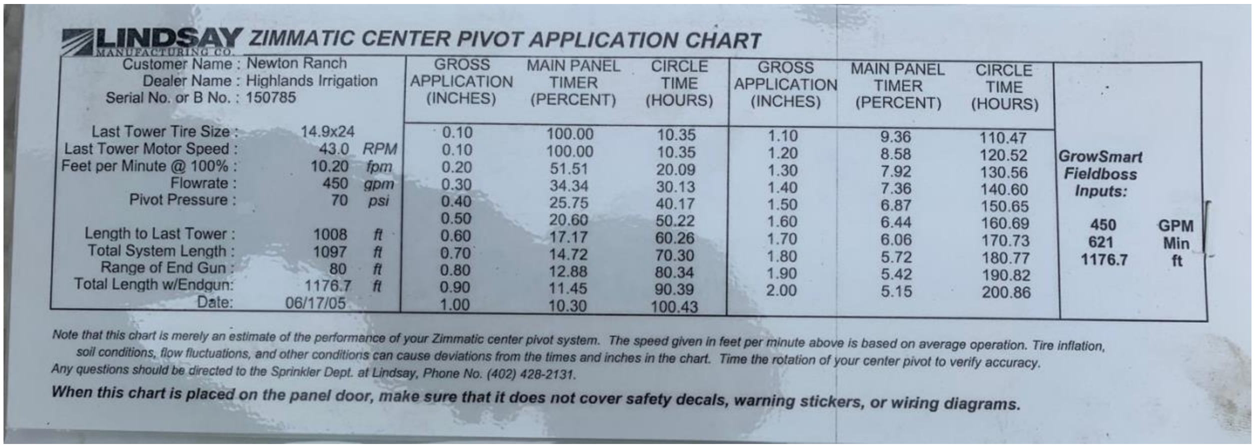
Other Items	Quantity	Unit Price	Total
Custom Spreading (AC)	300.00 Acres	$7.50	$2,250.00

Nutrient		Target Rate
N	Nitrogen	49.746
P	Phosphorus	19.898
K	Potash	19.898
S	Sulphur	11.939

Area (acres)	300.000
Rate (LBS/acres)	198.0
Density	58.3
Qty (Metric tonne)	26.939
Unit Price	$818.00
Subtotal	$22,036.10
Other Items	$2,520.00
Total Price	$24,556.10
Price/acres	$81.85

Figure A.1: 2012 Invoice from Okanagan Fertilizer for Newton Ranch showing nutrient composition and application rate of annual fertilizer.

Appendix B



LINDSAY MANUFACTURING CO. ZIMMATIC CENTER PIVOT APPLICATION CHART

Customer Name : Newton Ranch
Dealer Name : Highlands Irrigation
Serial No. or B No. : 150785

Last Tower Tire Size : 14.9x24
Last Tower Motor Speed : 43.0 RPM
Feet per Minute @ 100% : 10.20 fpm
Flowrate : 450 gpm
Pivot Pressure : 70 psi

Length to Last Tower : 1008 ft
Total System Length : 1097 ft
Range of End Gun : 80 ft
Total Length w/Endgun: 1176.7 ft
Date: 06/17/05

GROSS APPLICATION (INCHES)	MAIN PANEL TIMER (PERCENT)	CIRCLE TIME (HOURS)	GROSS APPLICATION (INCHES)	MAIN PANEL TIMER (PERCENT)	CIRCLE TIME (HOURS)
0.10	100.00	10.35	1.10	9.36	110.47
0.10	100.00	10.35	1.20	8.58	120.52
0.20	51.51	20.09	1.30	7.92	130.56
0.30	34.34	30.13	1.40	7.36	140.60
0.40	25.75	40.17	1.50	6.87	150.65
0.50	20.60	50.22	1.60	6.44	160.69
0.60	17.17	60.26	1.70	6.06	170.73
0.70	14.72	70.30	1.80	5.72	180.77
0.80	12.88	80.34	1.90	5.42	190.82
0.90	11.45	90.39	2.00	5.15	200.86
1.00	10.30	100.43			

GrowSmart Fieldboss Inputs:
450 GPM
621 Min
1176.7 ft

Note that this chart is merely an estimate of the performance of your Zimmatic center pivot system. The speed given in feet per minute above is based on average operation. Tire inflation, soil conditions, flow fluctuations, and other conditions can cause deviations from the times and inches in the chart. Time the rotation of your center pivot to verify accuracy.
Any questions should be directed to the Sprinkler Dept. at Lindsay, Phone No. (402) 428-2131.

When this chart is placed on the panel door, make sure that it does not cover safety decals, warning stickers, or wiring diagrams.

Figure B.1: Application chart for centre pivot sprinkler system present on field with study enclosures

Table B1: Sample Data from 2021 Irrigation Log

Date	Time	Hours at start up	Set percentage
11-May	18:00	10702.13	35
12-May	7:00	10705.43	35
14-May	8:00	10728.28	35
22-May	9:00	10740.6	35
30-May	15:30	10765.3	35
14-Jun	12:00	10780.21	35

See below for sample calculation of approximate irrigation applied throughout a study month.

Total hours running in May = 10780.21 – 10702. 31
= 77.90 hours

Circles completed in May = 77.90 hours / 30.13 hours/circle
= 2.585 circles

mm of water applied in May = 2.585 circles x 7.62 mm/circle
= 19.70 mm

Appendix C - ATTEMPTING TO QUANTIFY THE EFFECTS OF RODENT AND INSECT HERBIVORY ON THE PRODUCTION OF PERENNIAL CROPPING SYSTEMS

INTRODUCTION

Pest management is an important part of agricultural practices. Pests include insects, disease organisms, weeds, rodents, birds, and wildlife (Farm Practice 2014). Pest infestations of any type can result in huge expenses, either through loss of crop production or cost of pesticide application. Rancher’s production largely depends on the health of their crops and thus proper pest management is necessary to minimize costs to pest infestations.

Rodents, including mice, voles, rat, squirrels, and chipmunks, can cause severe damage to agricultural crops, resulting in major crop losses (Brown et al. 2000, Agriculture and Food 2015). It is estimated that a single pair of mice can eat more than two kilograms of food over a six-month period (AGRI-FACTS 2005). From this metric, it is apparent the effect rodent grazing can have on crop production. Rodents eat both vegetative plant material as well as seeds, and damage to crops caused by rodent grazing can occur at the level of seeding, plant growth, and feed storage. Rodent species that are granivorous can cause poor germination as a result of seed consumption while herbivorous rodents cause direct damage to plants by gnawing on tillers and leaves (Brown et al. 2007; Agriculture and Food 2015). Crop germination and growth can also be hindered by the construction of underground tunnels and runways that rodents use to navigate throughout fields. The multitude of effects of rodent infestations makes their control a priority for ranchers.

There are many different management techniques for dealing with these infestations, including live or snap trapping, keeping feed storage areas clean, and sealing off buildings so rodents cannot enter (AGRI-FACTS 2005). The previously listed strategies refer to management of areas that are inside infrastructure and are relatively easy to monitor. At a larger scale, for instance multiple fields used for crop production, rodent infestations can be harder and more expensive to monitor and control. Possible management strategies include seeding early and evenly to ensure rapid establishment of vegetation, increasing seeding rates, sowing seeds as deep as possible, and the use of a rodenticide (AGRI-FACTS 2005). These larger scale management strategies can be costly, requiring the purchase of larger quantities of seed, a supply of rodenticide, and the labour costs associated with these strategies. Often, ranchers will have to make a decision about whether the cost of the infestation is worth the cost of the management strategy.

Removal of animals is generally thought to reduce the amount of damage caused by these pests; however little research has been done to confirm this assumption (Brown et al. 2007). Previous research has attempted to quantify the effects of rodent infestations on crops in order to justify the implication of management strategies. Brown et al. (2000) studied the impacts of rodent pests on crop costs and damage. Crop damage was estimated by counting the number of damaged tillers within a sample. They found a relationship between rodent abundance and crop damage. A second study by Brown et al. (2007) further investigated this relationship using simulated rodent grazing. This work produced a linear relationship between the two variables of crop damage and rodent abundance, yet this theory remains to be validated. Excluding rodents from fenced plots and regularly monitoring the enclosed area is a potential way to validate this theory (Brown et al. 2007). Having an area where rodents are excluded allows the direct comparison to areas where rodents are present, allowing the assessment of rodent damage. If rodent-present areas are also monitored for rodent density, information would also be given on the relationship between crop damage and rodent abundance.

Insects are another pest of concern for ranchers in British Columbia as they can weaken plants by feeding on their seeds, leaves, or roots (NC State University Department of Entomology 2005). In the Cariboo-Chilcotin region, the pests causing the most forage destruction are grasshoppers; clear-winged (*Camnula pellucida*) and migratory (*Melanoplus sanguinines*) (Ministry of Agriculture 2015). These species are present every year, usually only causing light damage. However, when large outbreaks occur, extensive damage can be done. In the Chilcotin, large grasshopper outbreaks have been recorded in every decade since the 1890s (Climate Action Initiative 2018). Various management strategies exist to deal with grasshopper infestations. Cultural control methods include sowing seeds early, rotating crops, and tillage. These methods attempt to protect crops against grasshoppers without utilizing any chemical controls. If the cultural control methods are not successful at preventing an infestation, chemical control is likely the only option (Ministry of Agriculture 2015). Chemical control methods include a range of insecticides, varying for different types of crops. These insecticides can be quite expensive, and it is suggested that ranchers only utilize them when the cost of controlling the insect is less than or equal to the cost of forage loss (Ministry of Agriculture 2015). This again leaves ranchers with a decision to make regarding pest management strategies.

Pest infestations can cause major crop losses to agricultural producers. Better understanding the effects of rodents and insects on crop production will provide valuable information on crop losses. This can help producers decide whether implementing pest control is worth the cost and at what level of infestation these pest management strategies should be applied to prevent crop losses (Hangay et al. 2008). Quantifying the effects of pests on crop production remains an important question in agricultural research. More research on these pests is needed in order to provide farmers with management options and reduce global food security risk (Donatelli et al. 2017). This Appendix attempts to quantify the effects of rodent and insect herbivory on the production of perennial cropping systems. Quantifying the amount of crop yield lost to these pests will allow producers to assess the benefit of controlling these pests compared to the cost of crop losses.

METHODS

Site location

This research took place at the established study site on Newton Ranch, within the irrigated, fertilized enclosure (see Chapter 2). Within three blocks of the irrigated enclosure, additional 2 m x 2 m study plots included areas in which rodent and insect exclusion measures were taken. These plots were each assigned a mowing height at which they were mowed at for the duration of the study. See Table C.1 for a list of additional treatments added.

Table C.1: List of pest exclusion treatments and corresponding treatment codes added within irrigated, fertilized enclosure.

Code	**Treatment**
XM0	Small mammal fencing, insecticide, and mowed at 0 cm
XM10	Small mammal fencing, insecticide, and mowed at 10 cm
XM20	Small mammal fencing, insecticide, and mowed at 20 cm
XM30	Small mammal fencing, insecticide, and mowed at 30 cm

Rodent exclusion

In order to exclude rodents from plot areas, exclusion fencing was established around the perimeter of all XM treatment plots in May 2020. This fencing consisted of wire hardware cloth dug approximately 30 centimetres into the ground and extended thirty centimetres above ground surface. Tin flashing was attached to the top of the mesh around the perimeter of the plot, extending outwards approximately 15 centimetres, to prevent rodents from climbing over top of the fencing (Figure C.1). This fencing design was modeled after Animex® small mammal fencing, which is frequently used by conservation and construction industries to exclude unwanted animals (Animex® 2020).

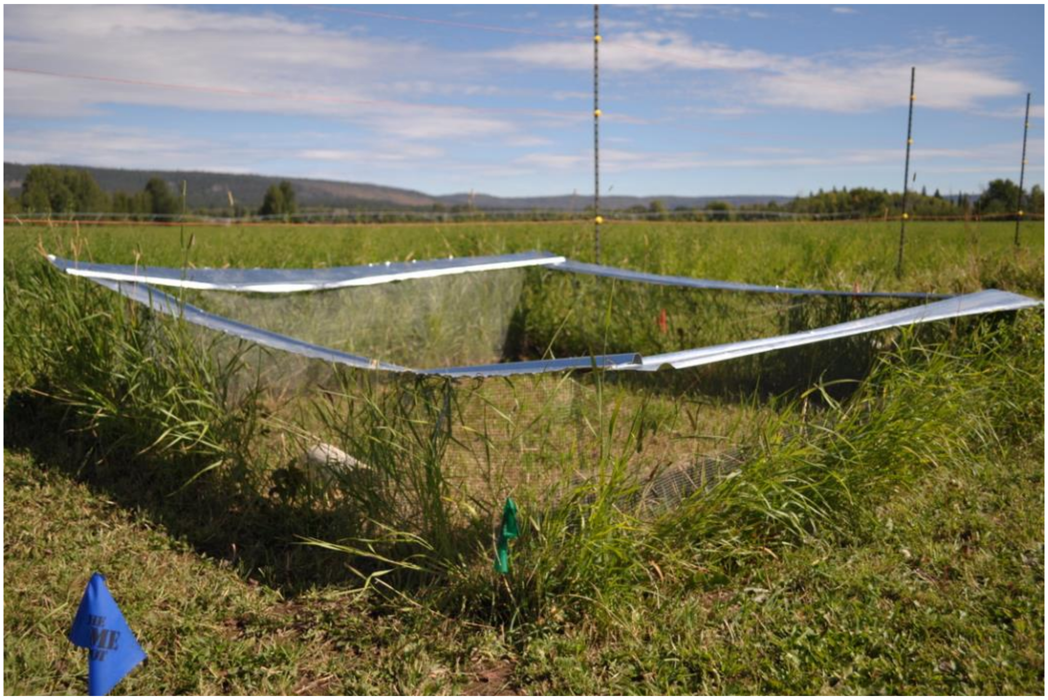


Figure C.1: Study plot surrounded by rodent exclusion fencing.

Once exclusion fencing was established, live trapping occurred within each enclosed plot to ensure the removal of all unwanted animals from within the plot area. Trapping protocols follow those suggested by the Ministry of Environment, Lands, and Parks (1998) to inventory small mammals. The trapping interval occurred for three days. No animals were captured throughout this trapping interval, so the excluded plots were deemed to be rodent-free.

Rodent activity monitoring

Track tunnels were used to monitor rodent activity within the study plots after the trapping interval had ended. Track tunnels consisted of 4-inch polyvinyl chloride (PVC) plastic piping cut in half and secured to a piece of plywood (31 cm x 12cm). Inside these structures, an ink pad and paper were placed to record an animal's tracks when they pass through the tunnel, recording their presence within the plot (see Figure C.2). The ink used for this experiment was a mixture of ferric nitrate, polyethylene glycol, a non-denaturing detergent, and water, following the recipe from King and Edgar (1977). The track-recording paper consisted of brown Kraft paper sprayed with a mixture of 5% tannic acid and 75% ethanol, also following King and Edgar’s (1977) protocol.

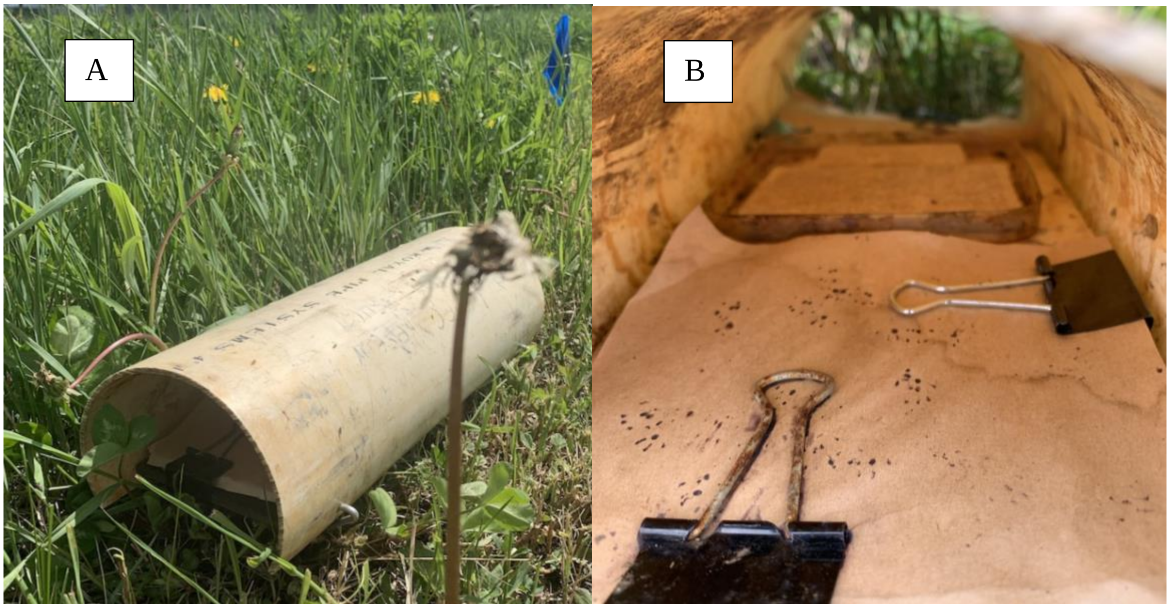


Figure C.2: Track tunnel design: A) PVC piping attached to plywood, B) Ink pad and paper setup showing resulting rodent prints.

Every two weeks the track tunnel papers were replaced, and the ink pad was replenished with fresh ink. The removed papers were scored with a ‘rodent abundance index’ from 0-5 (see Figure C.3). If rodent activity was noted within a plot that was surrounded by rodent exclusion fencing, fencing would be patched at places of suspected rodent entry and another trapping interval would occur within the plot. Rodent activity monitoring occurred from May to September 2020 and May to August 2021. Rodent abundance was summarized by taking the average of ratings given to each track tunnel paper at a certain time interval throughout the duration of the study.

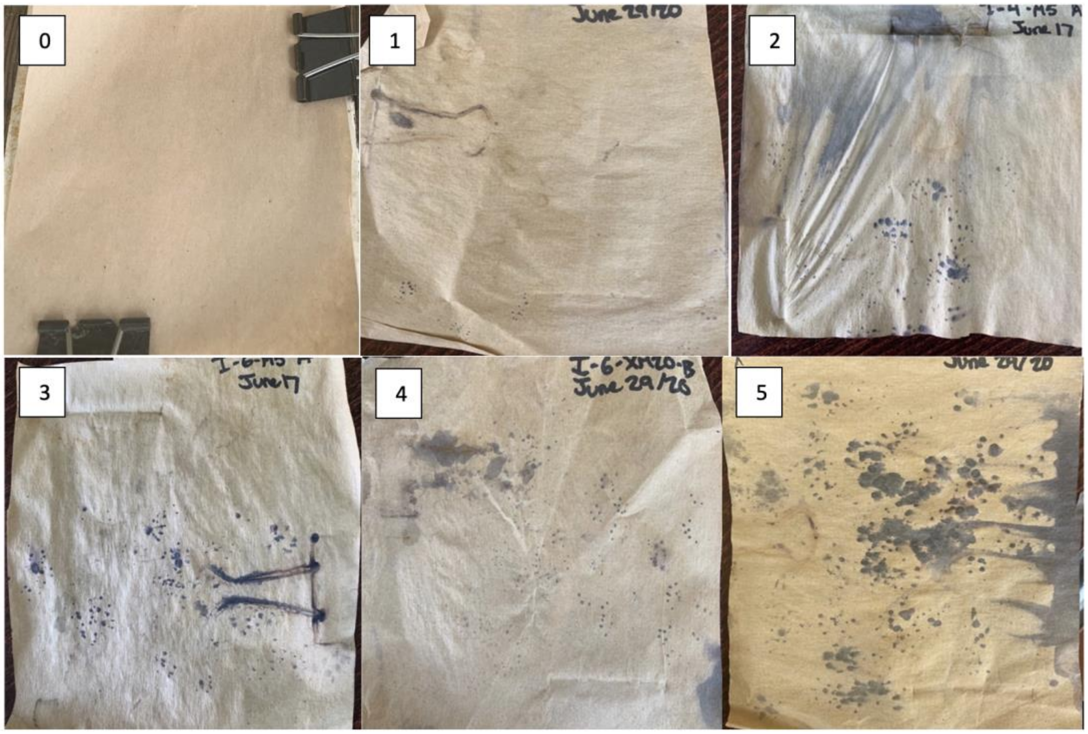


Figure C.3: Rodent activity scale from 0 (no rodent activity) to 5 (high rodent activity).

Insect exclusion

Insects were excluded from all XM treatment plots using an insecticide treatment. The product used was 50% Malathion liquid insecticide produced by Superior Control Products. Application occurred every two weeks following the application rate specified on the product label, scaled down to reflect the 2 x 2 m area of study plots. The resulting mixture was 10 mL of insecticide mixed with 3 L of water. 250 mL of this mixture was applied evenly to each XM plot using a vacuum sprayer bottle. Insecticide application took place from May to August of 2020 and 2021. Malathion was selected as it is a recommended insecticide for alfalfa crops for the control of grasshoppers, which are a priority pest within the region of the study (Ministry of Agriculture 2015).

Insect monitoring

At the time of vegetation survey throughout study years, plants within all study plots were inspected for signs of insect herbivory. Insect herbivory was recorded as present or absent for all vegetation surveys. Insect activity was summarized by taking the percent of plots that had seen insect herbivory at time of vegetation survey at each individual sampling event.

Mowing application

Due to the presence of the exclusion fencing, all XM treatment plots were unable to be mowed using the tractor and discbine mower as M treatment plots were. Instead, mowing was carried out using a STIHL FS 40 Grass Trimmer, using a ruler to measure to the appropriate cutting height (see Fig. C.4). All resulting clippings were then removed from the plot area using a rake.

Figure C.4: XM treatment plot being mowed using a STIHL FS 40 Grass Trimmer

Collection of field data

Throughout 2020 and 2021 growing seasons, data on plant species diversity, aboveground and belowground plant productivity, forage quality, and soil chemical and physical characteristics were collected. All protocols for XM treatment plots were consistent with the protocols detailed in Chapter 2.

Statistical analyses

All statistical analyses and figures were produced using R for Statistical Computing, version 1.4.1103 “Wax Begonia” (R Core Team 2021). In all cases, significance was defined by $p < 0.05$. Plant diversity, productivity, forage quality, and soil characteristics were analyzed using mixed effect model from the “lme4” package. For all models, mowing treatments were grouped to only compare between XM and M treatment effects. Timing, block, and mowing treatment were all included as random variables. Tukey’s HSD post hoc analyses were performed on all models using the “emmeans” package.

RESULTS

Rodent monitoring

Rodent abundance was recorded and summarized from track tunnel papers throughout 2020 and 2021 (Figure C.5). Throughout both years, unfenced plots saw consistently higher levels of rodent abundance than plots that were surrounded by rodent exclusion fencing. However, fenced plots still saw rodent activity throughout the duration of the study.

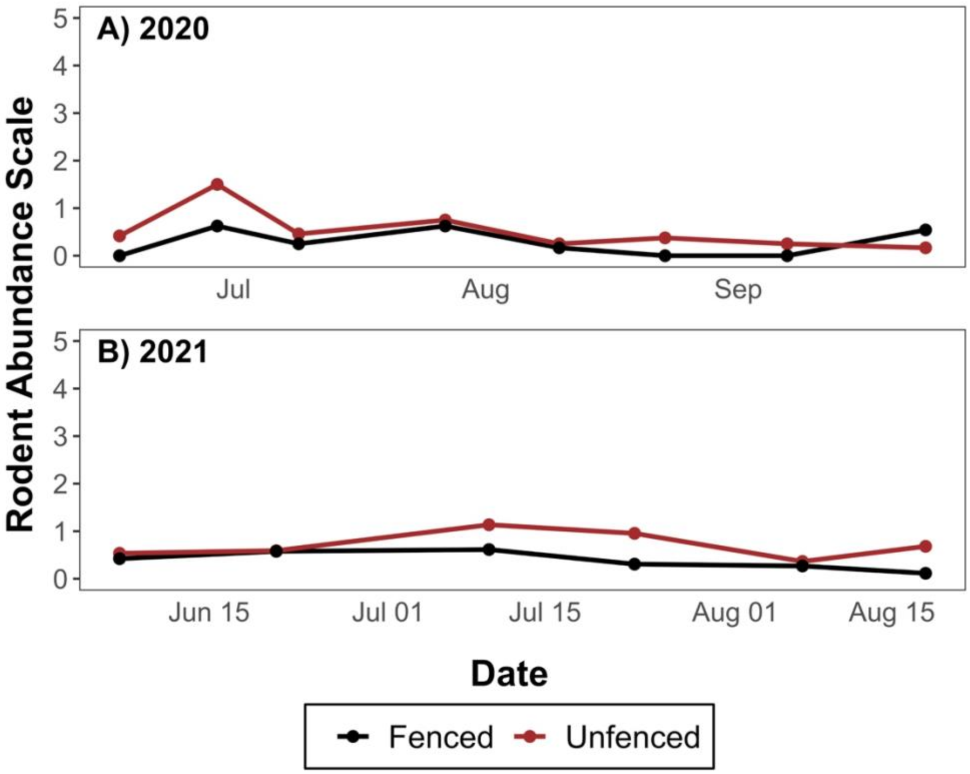


Figure C.5: Rodent abundance scaled from track tunnel papers within plots that had been fenced with rodent exclusion fencing and unfenced plots throughout A) 2020 and B) 2021.

Insect monitoring

Signs of insect herbivory seen within study plots were recorded at the time of vegetation survey throughout the duration of the study. The percentage of surveys showing signs of herbivory are displayed in Table C.2. At all survey dates, higher percentages of M plot vegetation surveys showed signs of insect herbivory than XM plot surveys. However, a notable percentage of XM plots also showed signs of herbivory at all sampling dates, except for August 2021.

Table C.2: Percentage of plant surveys showing signs of insect herbivory recorded at each sampling event throughout study duration.

		Survey Date			
		2020		2021	
	Treatment	June	August	June	August
Surveys with visual insect herbivory (%)	XM	37.50	20.83	12.50	0.00
	M	52.08	69.79	37.50	20.83

Plant community diversity and composition

No differences due to pest exclusion treatments were seen for plant community diversity and composition.

Aboveground plant productivity

No differences due to pest exclusion was seen for biomass production throughout the duration of the study.

Plant height was shown to be affected by pest exclusion treatments. XM plots showed significantly taller shoot height than M plots ($F = 19.32$, $p < 0.0001$, Figure C.6).

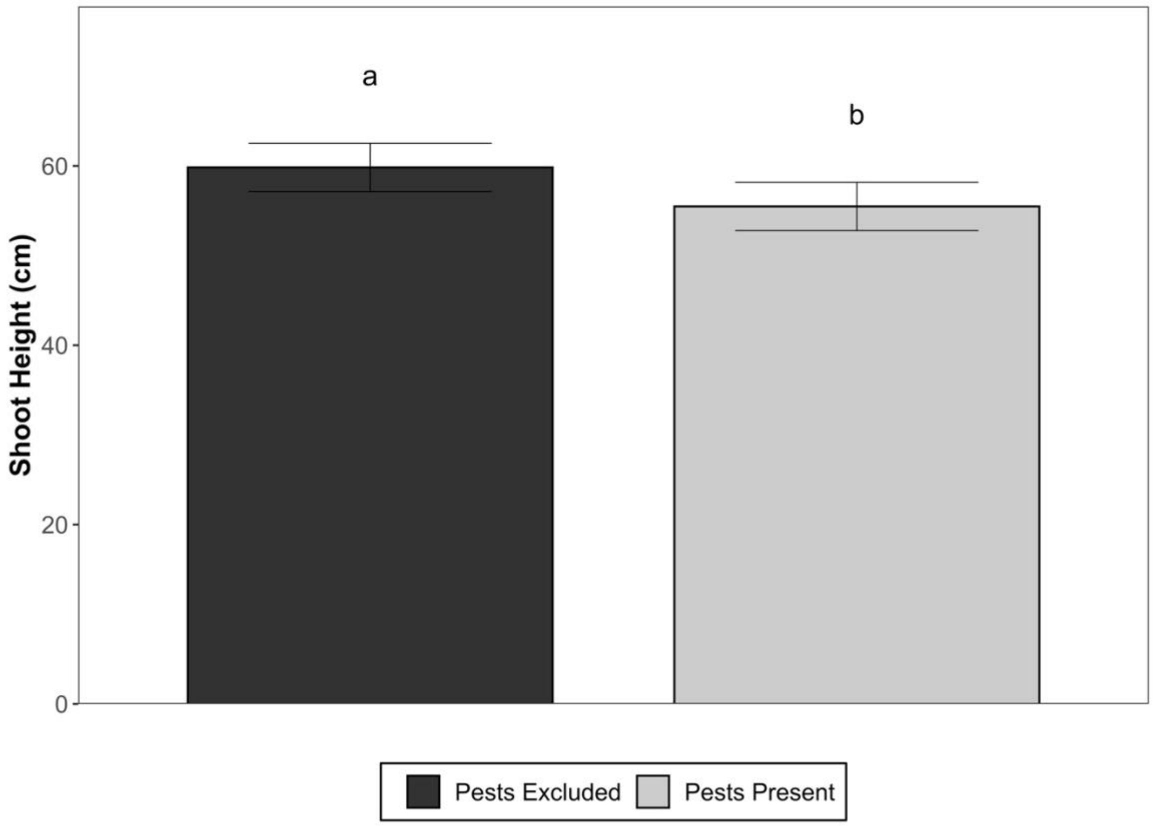


Figure C.6: Plant height grouped by treatment and timing, comparing between plots that had been excluded from pests and plots where pests were present, error bars represent 95% confidence intervals, significant differences are denoted by different lowercase letters as determined by post-hoc Tukey test following ANOVA ($p<0.05$).

Belowground plant productivity

No differences due to pest exclusion treatments were seen for values of root biomass.

Soil characteristics

No differences due to pest exclusion treatments were seen for soil carbon, nitrogen, or organic matter.

DISCUSSION

Limited effects on plant productivity were seen due to pest exclusion measures in this study. This was likely for two reasons: 1) Pests were not completely excluded from study plots throughout the duration of the study, and 2) pests were not present at high enough volumes to cause declines in crop yields.

Both rodent and insect exclusion measures were successful at lowering levels of pest activity seen within XM plots compared to M plots. However, pests were not completely excluded, and some levels of both rodent and insect activity were seen throughout both study years. Because rodents and insects were not properly excluded from any plots, differences in productivity cannot be equated to activity from these pests. Pests were also not seen at high volumes outside of the excluded plots, further increasing the unlikelihood of pest activity causing the difference in plant height seen in this experiment.

A more likely explanation for the difference in plant height was the effect of shading caused by the rodent exclusion fences. These fences protruded high above ground level and with attached tin panels, caused a fair amount of shading on the pest exclusion plots. The shaded conditions caused increases in competition for light, which is a major resource within plant communities (Grime 1979). Taller plants have better access to light and thus competition for light favours increases in plant height (Westoby et al. 2002), which occurred within plots surrounded by rodent exclusion fencing. This increase in height came at a cost. Metabolic investments shifted to grow tall stems and associated support structures, decreasing investments in other areas of growth, such as increasing leaf area or number of stems (Westoby et al. 2002). This was seen in this experiment when shading caused a significant increase in plant height, but no differences were seen for biomass production.

CONCLUSION

Pests were not able to be successfully excluded from study areas and thus the affect of rodent and insect herbivory on perennial crop production was unable to be assessed. Further research should explore methods of pest exclusion that are capable of completely removing pest activity from study areas to properly assess damages caused to crops as a result of rodent and insect presence. It was shown that the rodent exclusion fencing utilized for this experiment caused significant shading. Future design of exclusion fencing should account for these effects. While pest management remains an important strategy within the agricultural industry, this experiment was unable to produce meaningful results pertaining to this issue.

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Appendix D - Detailed Site Maps

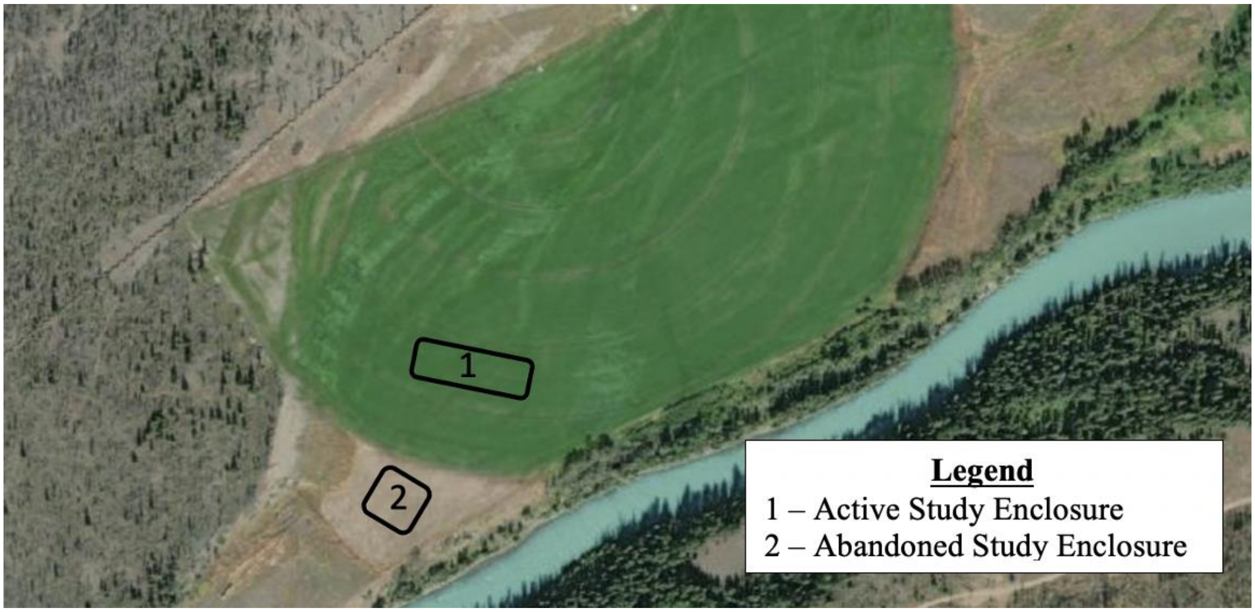

Figure D.1: Location of study enclosures within study field, satellite imagery provided by iMap BC.

Figure D.2: Layout of study blocks within active enclosure, satellite imagery provided by iMap BC.

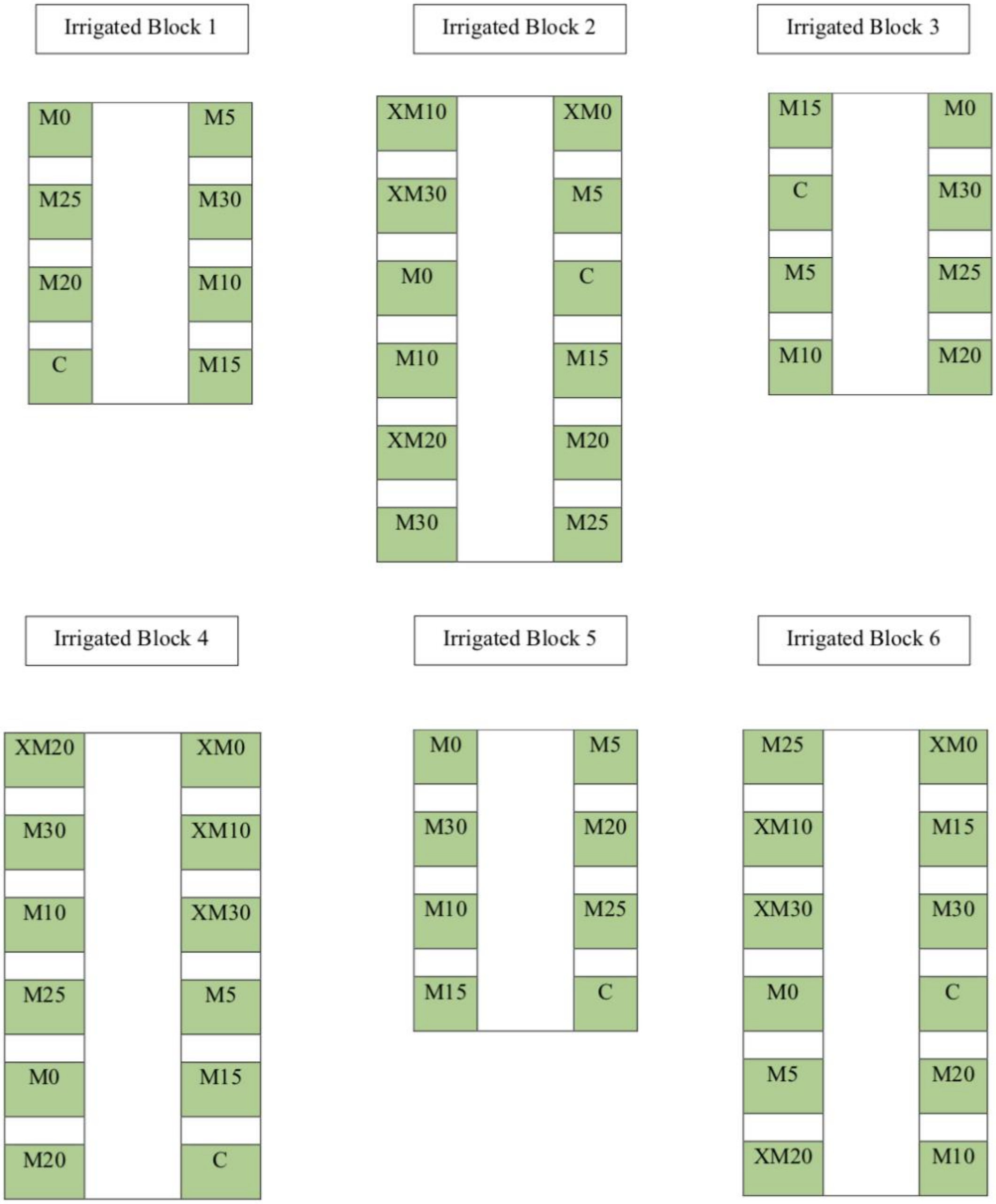

Figure D.3: Assignment of mowing treatments within each study block of the active enclosure, displaying randomized block design.

Figure D.4: Layout of study blocks within abandoned enclosure, satellite imagery provided by iMap BC.

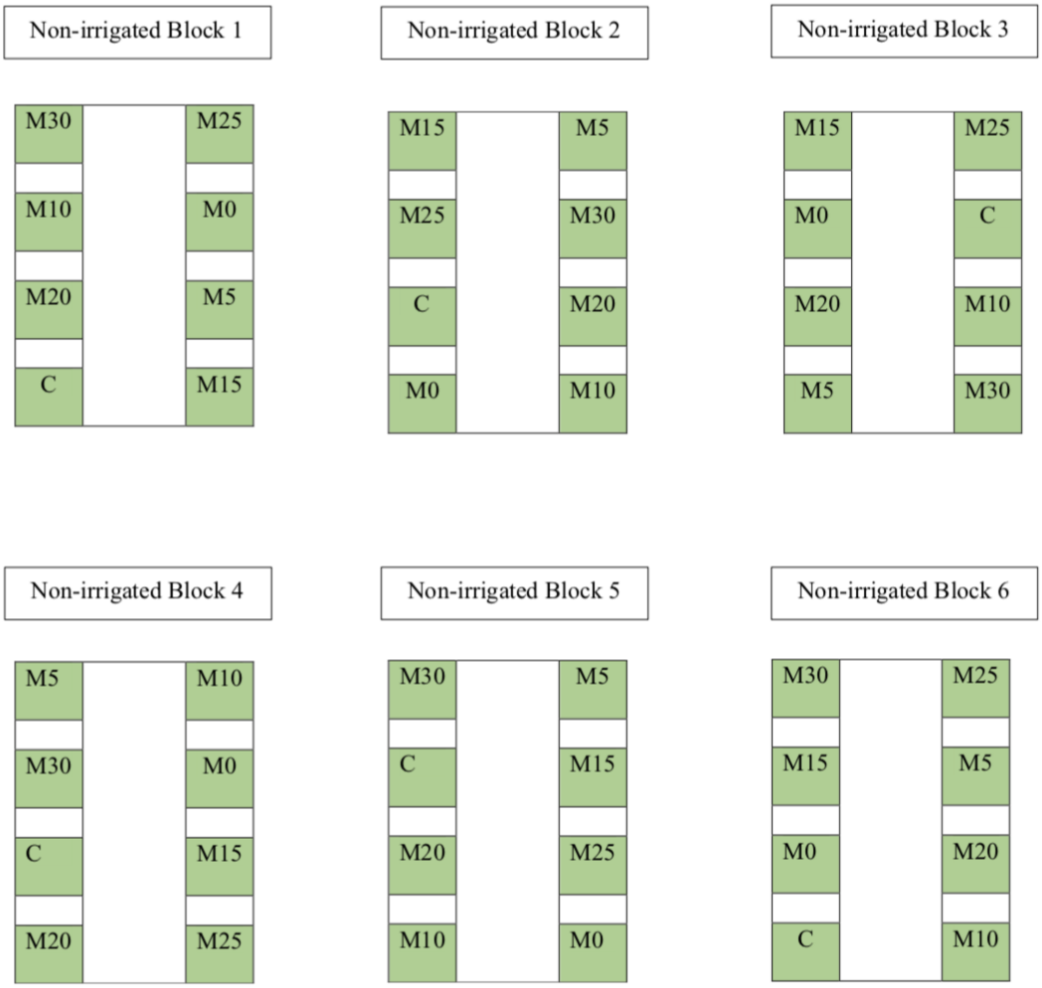

Figure D.5: Assignment of mowing treatments within each study block of the abandoned enclosure, displaying randomized block design.