UTILIZING PASTURE RESOURCES FOR SUB-ARCTIC AGRICULTURE: SUSTAINABLE

LIVESTOCK PRODUCTION IN ALASKA

By

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Abstract

It is estimated that the globe must produce 100% more food in the next 50 years to meet growing demand while addressing the compounding challenge of climate change. One potential solution to this challenge is to produce more on existing agricultural lands and put more land into production. The extremely cold and dry climate that characterizes much of Alaska has all but removed the state from the state and national discussions of agricultural production and development. Yet despite this apparent incompatibility with traditional agricultural models, some of the largest wild herds of grazing ungulates are indigenous to Alaska - and thriving. This is both a testament to the resilience of grazing systems in general as well as a statement to the suitability of grazing systems specifically for Alaska.

To shift the paradigm towards ecological and economic sustainability, we need to develop sustainable agricultural strategies that are specific to this unique ecosystem. A two-fold approach was used in this body of research: Is there an indigenous livestock species that could be economically feasible enterprise option? Is there a grazing management regime for sub-arctic Alaska that would improve ecosystem services and optimize pasture resources?

I conducted an economic feasibility study of farming muskoxen (*Ovibos moschatus*), a uniquely adapted arctic ungulate, to address the first question. An enterprise budget was used to estimate the fixed and variable costs and to model different revenue scenarios using six different combinations of qiviut, sold as raw fiber or value added yarn, and livestock sales to estimate the total economic potential of farming muskoxen at two scales, 36 and 72 muskoxen.

Farming muskoxen was economically sustainable under several revenue scenarios. The most profitable scenario for either herd size was selling all the qiviut as value added yarn coupled with livestock sales. The enterprise was profitable at either scale assuming all the yarn sold at full retail price. If no livestock were sold, selling the total qiviut harvest as yarn was the

only profitable option. When selling raw fiber alone, the break-even point was at a herd size of 124 muskoxen. Economies of scale accounted for a decrease in costs of approximately 21% overall, 30% in labor, and 23% in herd health, as the herd doubled in size.

To address the need for grazing management strategies that are both environmentally and economically sustainable in Alaska, I conducted a study to evaluate the potential of intensively managed rotational grazing (IMRG) regimes on sub-arctic pasture. This regime is designed to mimic the short but intense grazing of wild, migratory ungulates that could enhance ecosystem function while optimizing pasture usage and forage growth. I conducted simulated grazing, applied using IMRG methodology, to evaluate above and below ground response to an IMRG regime and to gain insight on the role of grazing disturbance mechanisms on sub-arctic soil and plant health.

A full factorial experiment of muskox dung/urine deposition (M), simulated trampling (T), and herbivory (H) (forage clipping), mimicking IMRG timing and intensity, was conducted at the Large Animal Research Station (LARS), UAF. I used a randomized block design with 96-1 m^2 plots in two established pastures with different soil types, over the 2014 and 2015 grazing seasons. I documented a treatment effect on soil parameters, forage growth, and percentage of bare soil ($p < 0.05$). Soil nitrogen cycling and the Haney Soil Health Index both increased in plots that received a combination M and T or MT and H. The forage yield was consistently increased by MH, MTH, and H treatments. Although the MT and T treatments had a negative impact on forage yield, they had the largest reduction in the amount of bare ground. The data from this simulated study suggest that theories that underpin the IMRG method are potentially useful to producers, in the unique Alaskan subarctic environment.

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Introduction

Global agriculture faces some immense challenges in the next 50 years. It is estimated that the world population is going to increase to nine billion people by the middle of the century (Godfray et al., 2010; Pretty et al., 2010). While the last century has seen enormous increases in food production, it is estimated that 70-100% more food will have to be produced to feed the growing population (Pretty et al., 2010). Although modern industrial technologies and techniques have dramatically increased food yields, many of the negative impacts on the environment and rural communities have yet to be accounted for (Ikerd, 1993; Kornegay, 2010). There is a large consensus that the dependence on fossil fuels and non-renewable resources is not sustainable (James, 2006). The challenge of producing more food while addressing the resource dependency is further intensified by the climate change crisis. Currently agricultural production contributes one third of the greenhouse gases released into the atmosphere, the driving factor of climate change (Godfray et al., 2010; Change, 2014). The reduction of productive agricultural land due to desertification, urbanization and soil erosion, intensified by the effects of climate change, has further increased the pressure to produce more with less resources (Godfray et al., 2010). A paradigm shift toward sustainable intensification of agriculture may become the only viable option (Godfray et al., 2010).

Livestock production has been cast as both a positive and negative influence on these challenges, from degrading the environment and food security, to reducing poverty and reversing desertification (Savory, 1983; De Haan, 2001). A livestock revolution is expected to shape agriculture in the coming decades (McGilloway, 2005). Greater affluence in the developing world is expected to vastly increase the demand for meat, dairy products, and fish (Godfray et al., 2010; Pica-Ciamarra et al., 2014). While the demand is expected to increase, climate models predict substantial impact to global rangelands that could change the ecosystem

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services that livestock producers rely upon (Joyce, 2013). This has prompted a call for ways to address the effect of climate change in grazing lands with sustainable mitigation and adaptive approaches (Joyce, 2013). These actions and policies must be developed at every scale from global initiatives to locally (Joyce, 2013). Locally developed solutions are more likely to be in synchrony with the environmental and social context of a region, while providing economic sustainability for producers (Ikerd, 1993; Godfray et al., 2010; Pretty et al., 2010). Some of the suggested adaptation strategies for rangeland management include flexible herd management and alternative livestock breeds or species (Joyce, 2013).

The 2005 Millennium Ecosystem Assessment broadly classifies Alaska as a Polar Ecosystem, characterized as being frozen most of the year and underlain by permafrost. Despite this bleak portrayal, some of the largest herds of grazing ungulates are indigenous to Alaska - and thriving. This is both a testament to the resilience of grazing systems in general as well as a statement to the suitability of grazing systems specifically for Alaska. Yet Alaska is one of the lowest agricultural producing state in the United States and has limited land currently in pasture for livestock production (Dinkel, 2012). The Alaskan economy is dependent on resource extractive industries such as oil extraction, mining, and commercial fishing (Fried, 2013). Agriculture production has been constrained by extreme climatic conditions, expensive imported farm inputs, a lack of research into farming practices appropriate for northern environments, and competition from the high yields and low prices of global and domestic markets (Meter, 2014). As environmental, economic, and social factors begin to challenge the viability and benefits of an oil dependent state economy, along with grave concerns about food security (Meter, 2014), a renewed interest in sustainable agricultural production is emerging (Agriculture, 2009).

The motivation for this research originated at the 'Sustainable Livestock Production in Alaska Workshop', sponsored by Sustainable Agriculture Research and Education (SARE)

program of the United States Department of Agriculture (USDA). Local stakeholders who attended the workshop identified the following needs: improve management of on-site resources through better grazing practices; develop grazing strategies appropriate for Alaskan ecosystems; maximize economic resources for potential niche products; and do more research on sustainable, alternative livestock species (Rowell, 2011). Of these community identified needs, we chose two different but complimentary research topics that address several different facets of sustainability; economic profitability, environmental concerns, resource conservation, and socially appropriate strategies. My thesis consists of two independent chapters which:

1. Evaluate the economic potential of farming an indigenous livestock species, the muskox (*Ovibos moschatus*) for their fiber (qiviut)
2. Examine the potential impact of intensively managed rotational grazing (IMRG) on forage and soil parameters in sub-arctic Alaska

The first chapter, **Farming muskoxen for qiviut in Alaska: A feasibility study**, addresses the first question in evaluating the economic potential of farming a livestock species uniquely adapted to the sub-arctic environment. The extreme climate and geography of Alaska increases the challenge of ecologically and economically sustainable agriculture when traditional agriculture models, using species developed for more temperate climates, are imposed on the sub-arctic landscape. Muskoxen are a goat-like ruminant, indigenous to arctic regions. Because they evolved in the north, they require no protection from the cold. They eat snow instead of drinking fresh water during the winter months and thrive on local forage. They are able to maintain adequate body mass on a diet of low protein forage and require half the daily dry matter intake of cattle when scaled for size (Adamczewski et al., 1994). Their fiber, called qiviut, is their primary defense against the harsh arctic cold.

Qiviut fiber rivals cashmere for softness and warmth. This luxury fiber has been harvested annually by a small number of farms since the 1960's (Flood, 1989). A small niche market

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currently exists for this fiber, yet commercial farms have struggled to become established. In the last few decades, changes to the fiber processing industry, expansion of online markets and marketing have changed the economic potential of muskox farming. In chapter one, we detail the potential of a muskox farming operation using an enterprise budget to estimate the costs and revenues as a first step toward the sustainable development of this livestock industry. Our analysis was based on literature that examined the profitability of alternative livestock or alternative enterprise structures such as bison, alpaca, small scale sheep production and heritage breeds of cattle. (Teal, 1972; Foulke, 2001; Kumm, 2009; Bond, 2011; Swan, 2013) Our goal was to lay the foundation for further in depth analysis while providing potential livestock producers with useful foundation information as a prerequisite to establishing their own enterprise.

The second chapter, **Sustainable livestock production in sub-arctic Alaska: Plant and soil responses to simulated intensive grazing**, addressed a knowledge gap for grazing management techniques appropriate for northern latitudes. Healthy productive pasture ecosystems are the key to providing high quality forage for raising livestock, maintaining good ecosystem function, and minimizing dependence on high cost imported feed and fertilizer. Grazing management affects plant composition, nutrient cycling, hydrological pathways, soil structure, and soil biotic communities in pasture ecosystems (Wang, 2006; Teague *et al.*, 2011). Grazing has the potential to generate either positive or negative impacts on these parameters based on the intensity and frequency of the grazing event. The IMRG method proposes to mimic the short but intense grazing of wild, migratory ungulates (Savory, 1983; Teague, 2013). This method is purported to increase the carrying capacity of the land compared to traditionally recommended continuous grazing levels, while enhancing healthy ecosystem function (Barnes et al., 2008; Teague et al., 2011). This method is described as a means by which agricultural animals could provide the same ecological function as wild ungulates in grassland ecosystems

thereby attaining two, often conflicting goals of ecosystem conservation and economic profitability (Savory, 1999).

Grazing disturbance occurs via three mechanisms, herbivory, trampling and dung and urine deposition. Neither the relative effects nor the interaction between these mechanisms are frequently examined (Kohler, 2005; Sorensen, 2009). As IMRG regimes are implemented on the landscape to maximize productivity and sustain healthy ecosystem function, the ability to understand and anticipate the impact on forage production, soil characteristics, and nutrient cycling from these grazing mechanisms is critical for management decisions.

The IMRG regime places emphasis on the role of trampling and its ability to incorporate organic residues into the soil profile (Savory, 1999; Teague *et al.*, 2011). Separating the grazing mechanisms provides an opportunity to evaluate the role of trampling in a sub-arctic environment. There is evidence that intensive grazing by reindeer and muskoxen increases primary production in arctic and sub-arctic environments (McKendrick, 1981; Olofsson et al., 2001). These environments are characterized by their extremely cold and dry climate, and the slow decomposition rate of organic residues. How important is the role of trampling for the incorporation of organic residues in the soil profile? Do the faster nutrient cycling pathways of the ungulate digestive system have an intensified impact? We conducted a simulated study to evaluate these mechanisms under an IMRG regime. We hypothesized that the IMRG regime would have a positive impact on biomass production and soil nutrient cycling, while having a negative impact on soil physical characteristics. Our goal was to provide baseline information, providing a deeper understanding of the theoretical underpinning of IMRG, determine the role of the grazing mechanisms themselves and guide the implementation of a live grazing trial.

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Chapter 1 Farming muskoxen for qiviut in Alaska: A feasibility study[1]

1.1 Abstract

Muskoxen (*Ovibos moschatus*) have been farmed since the 1960's for their fiber, called qiviut, a luxurious and highly valued underwool that is their primary insulation during the arctic winter. Muskoxen are uniquely adapted to the arctic. They thrive on local forages, do not require protection from the cold and adapt well to many traditional husbandry practices. While muskoxen can be farmed for qiviut, the question remains whether it is economically feasible and potentially sustainable enterprise in subarctic Alaska. This feasibility study was conducted using an enterprise budget at two scales, 36 and 72 muskoxen, to estimate the principal costs and model different sales combinations. Under several revenue generating scenarios, the feasibility study indicated a potential for economic viability of an established enterprise. The most profitable scenario for either herd size was selling all the qiviut as value-added yarn, coupled with livestock sales. In the absence of selling livestock, the enterprise was profitable at either scale assuming all the qiviut sold as yarn. Selling qiviut, solely, as raw fiber was not projected to break even under the model parameters. The modelled enterprise emphasized the importance of value added goods, economies of scale, low or zero opportunity costs, and the potential of a more active livestock market.

1.2 Introduction

Sustainable agriculture denotes site specific farming systems that provide for human food and fiber in perpetuity by enhancing the environment, conserving scarce resources, enriching personal lives and communities, and ensuring economic viability for the long term (Kornegay et al., 2010). In addition to being limited by the obvious climatic and geographical constraints, sustainable agriculture in Alaska must also compete with the high yields and low prices of agricultural products from the contiguous United States. The ecological and economic challenges of sustainable agriculture in Alaska are most evident when farming methods and species developed for temperate climates are imposed on a northern landscape. In order to shift this paradigm, we need to embrace a broader vision of agriculture that includes indigenous, non-traditional species and farming practices, while exploring niche markets.

The muskox (*Ovibos moschatus*), a native arctic ruminant, fits these primary criteria (Rowell et al., 2007). Muskoxen are indigenous to the Arctic. They produce a luxury fiber, qiviut, for which niche markets currently exist, while being well adapted to the extreme climate and landscapes of the circumpolar north. We know that muskox farming supports two of the three components of the sustainability triad: ecological compatibility and social/cultural acceptance in Alaska. This paper addresses the economic viability of farming muskoxen, the third, critical criteria for sustainable agricultural practices.

Muskoxen were reintroduced to Alaska in the 1930's and today wild populations can be found north of the Brooks Range, on the Seward Peninsula and on Nunivak Island (Jones and Perry, 2013). The Alaska State Legislature declared muskoxen an agricultural species that can be legally farmed in the state (Alaska State, 2014). The emerging consensus from 50 years of muskox farming is that husbandry is not inherently different from that of more traditional livestock raised in northern climates (J. Blake, pers. comm. 2014).

Muskoxen generally share the temperament and nutritional requirements of goats, and the fencing and handling infrastructure for bison and other non-traditional livestock (J. Blake, pers. comm. 2014). Because they are adapted to circumpolar habitats, muskoxen require no shelter from subzero temperatures or fresh water once there is sufficient snow; adaptations that reduce dependence on heat and water utilities, and infrastructure. This is coupled with their ability to maintain adequate body mass on low protein forages through a combination of low metabolic requirements and efficient digestion, in contrast to cattle, which require more than twice the daily dry matter intake of muskoxen when scaled for body mass (Adamczewski et al., 1994). The ability of the muskox to successfully graze marginal lands and utilize low protein forage enables producers to exploit previously unproductive land holdings. This is an important consideration in Alaska where land is often unimproved, difficult to access, and costly (or impractical) to convert to traditional agricultural or commercial uses.

Adult muskoxen weigh an average of 300 kg (males) and 200 kg (females) with a life expectancy for females and castrates that can exceed 20 years (White et al., 1997). Females breed once they reach 180-227 kg (2-3 years old) and are capable of producing one calf per year (White et al., 1997). In Fairbanks, rut typically begins in August and breeding is usually complete by September. Calves can be left with a tame mother or weaned between 2.5 - 4 months and then offered food treats (or dilute milk substitute) to facilitate handling (Rowell, 1990).

The muskox pelage constitutes their primary adaptation to the cold: long primary guard hairs covering a 4-8 cm thick, layer of secondary fibers or underwool, named qiviut by the indigenous people (Robertson, 2000). Every spring qiviut is shed in a highly synchronous manner enabling it to be combed in luxuriant sheets from farmed animals (Figure 1) (Rowell et al., 2001). Individuals annually shed 1.3-2.8 kg of qiviut, approximately 1% of their body weight. Qiviut is considered a rare, luxury fiber, comparable to fine cashmere, vicuna, guanaco (McGregor, 2012), and provides the economic potential for muskox farmers (Rowell et al.,

2001). Qiviut's luxury characteristics, scarcity, and unique origin, translate into high prices on fiber markets.

There are three sources of qiviut: naturally shed and collected off the tundra, shaved or plucked from the hides of harvested wild animals, and combed from farmed muskoxen. Wild muskox populations provide the bulk of the fiber for today's qiviut industry. From these sources, qiviut yarn, garments, and accessories are successfully being marketed to established niche markets over the Internet, through specialty boutiques, and through popularity with tourists that visit Alaska (Cortright, 2006; Kissel, 2009). Luxury garments made of qiviut have achieved a celebrity following with suits being sold for as much as $25,000 (Kissel, 2009).

The economic potential of muskox farming has been recognized in North America for over 60 years (Wilkinson and Teal, 1984), yet early muskox farm enterprises struggled to have their relatively small amounts of qiviut processed into value added goods, gain access to developing niche markets, and find support for herd health and veterinary care. Many of these challenges have been diminished by advances in small custom mill processing, Internet sales, and research on muskox health and husbandry.

To date, the lack of an active market for muskox livestock, substantial startup costs, and the risk associated with farming non-traditional species remain the largest barriers to establishing new farms in Alaska. In light of the progress and potential as well as the barriers and risk that influence muskox farming, an assessment of economic viability is a critical first step in establishing sustainable development. In this paper, we have modelled the principle economic variables of a hypothetical, established farm in order to provide a basis for evaluating the sustainable economic potential of such an enterprise.

1.3 Methods

The feasibility study was conducted using an enterprise budget to estimate the principal fixed and variable costs, and model different revenue scenarios. The economic data for this enterprise budget have been extrapolated from two non-profit muskox facilities in Alaska, the only farms currently selling commercial quantities of qiviut. Cost and revenue information was based on 2012-2014 data for Robert G. White Large Animal Research Station (LARS) and 2013 data from the Musk Ox Development Corporation (MODC). The estimates used represent a range between the two data sets. Interviews with experts and stakeholders in the field of muskox husbandry, and cost quotes from suppliers in Fairbanks, Alaska were used to project production costs that are not well represented by the non-profit facilities. The enterprise budget constructed from these estimates was modelled on enterprise budgets from the bison and alpaca industries (Foulke et al., 2001; Bond, 2011). The resulting enterprise budget does not represent any particular facility or farm but rather a hypothetical farm whose operation is described by an amalgamation of the multiple sources listed above. It is intended to provide a general understanding of the commercial viability of farmed qiviut production in the north and the approximate costs and revenues associated with this endeavor.

1.3.1 Enterprise Budget

The enterprise budget was built upon a number of assumptions detailed below. The budget was constructed at two scales, 36 and 72 muskoxen on 16.19 ha and 32.38 ha, respectively, to accommodate a range of operation sizes. At the time of data collection LARS and MODC had 25 and 72 muskoxen, respectively. The MODC facility, with 72 muskoxen, represents an upper limit to potential economies of scale as the number of muskoxen was approaching the infrastructure and land area limitations of that facility (J. Curtis, pers. comm. 2014). The smaller scale of 36 muskoxen was chosen as a 50% reduction of the larger

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operation. The land requirements were based on the ability to feed each of the herd sizes the required 1320 kg of dry weight forage during summer season (120 d) without supplemental hay and a pasture productivity of 3000 kg/ha. All variable costs were assumed linear. All costs and revenues are reported in U.S. Dollars. Tables 1 and 2 detail operating and depreciable costs respectively, while Tables 3 and 4 present the value of the qiviut harvest per kg and potential revenues.

1.3.2 Projected Costs

Muskoxen consume approximately 4-5% of their body weight per day in forage dry weight during summer (June-Sept) and 2-3% during winter (Oct-May). This budget assumes sufficient pasture for grazing an average of 11 kg dry weight forage/animal/d over 120 d of summer and an average of 3.5 kg of hay/animal/d required from October to May based on LARS mean herd body weight of 176 kg, (used to calculate qiviut yield/kg body weight). Hay was estimated at $190 per 363 kg bale based on LARS costs. Pellet supplementation is essential all year long to compensate for pasture and hay deficiencies. A specially designed muskox ration is fed at a rate of 0.75 kg/animals/d for an annual total of 272 kg ration. Pelleted feed cost $20.50 per 22.7 kg bag.

It is assumed in the budget that the herd of muskoxen is consistently handled, such as the MODC herd, where early weaning of calves is not necessary. Labor estimates were based on MODC and LARS practices and are similar to the sheep industry where additional seasonal lambing and shearing inputs are required (Kumm, 2009). In this analysis, the labor requirement is assumed to increase by approximately 50% as the herd increases by 100% (Kumm, 2009). The model assumes a herd of 36 muskoxen with a full time owner present and a year round part-time employee, to assist with handling, combing, calving, and taming animals. At the scale of 72 muskoxen, the permanent part-time position transitions to a full-time position during the summer season (mid May-August) with additional part time summer employee required to meet

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the increased labor demands. The full time owner was not included in the labor costs as they are the recipient of the stream of revenues from the enterprise. The year round, skilled farm employee was budgeted at $15 per hour and seasonal, unskilled employee was budgeted at $10 per hour. Payroll taxes were estimated to be 26%, based on the requirements for Alaska. Consistent labor inputs for taming new calves and for the labor intensive spring qiviut harvest and calving season are necessary to maintain a high level of productivity.

A comprehensive herd health program, developed in conjunction with a local veterinarian, establishes nutritional regimens and husbandry practices, sets and monitors goals for weight gain, reproductive performance and production parameters. The program is designed to meet production goals and mitigate risk. The management assumptions in this modelled enterprise are based on the herd health program established at LARS through the UAF Animal Resources Center and incorporates associated veterinary fees. The herd health costs contain both fixed and variable cost components.

An annual fixed cost of two, 2-hour veterinary consultation visits at $200 per hour enable planning, analysis of records, review of vaccination and parasite control schedules, breeding and reproductive health, nutritional assessment and monitoring, and routine health maintenance. In conjunction with recording weight and reproduction, qiviut yield and qiviut characteristics provide an indirect measure of herd health. The cost of measuring the fiber staple length profile to monitor qiviut characteristics was $9.50 per sample (Yocom-Mccoll Testing Laboratories, Denver CO, 2015). A separate, variable cost of $15 per animal for emergency veterinary calls, was assessed for unforeseen illness, injury and calving complications. Annual vaccinations costs were included at $3.30 per animal and were assumed to be administered by farm employees along with routine care.

The opportunity cost of land in the enterprise budget is based on the potential cash rent the land owner could receive if they chose not to farm the land themselves. This is a

representation of the income available to the owner in its next most highly valued use (Hofstrand 2008). As muskoxen are able to graze land not well suited for other agricultural or commercial uses, the cash rent and hence opportunity cost to the land owner to farm muskoxen is assumed to be zero. The land is considered an appreciating asset and not included in the costs. Property taxes represent the cost of holding the land. Land under agricultural production is subject to a reduced property tax rate under the Fairbanks North Star Borough Farm Use Exemption Program and therefore could reduce the owners cost of holding land if it is not currently under agricultural production.

The enterprise budget assumes that all capital is borrowed at a commercial loan interest rate of 7%. All costs were totaled and a simple interest rate of 7% was applied to determine the capital cost of the enterprise. The 7% interest rate was applied to the depreciable costs in order to account for borrowing costs associated with the upfront purchase of depreciable items. (Individuals interested in constructing a startup muskox operation will need to adjust this assumption based on available loan rates for operating and fixed capital and loan cost estimates based on separate loan schedules for assets).

Depreciation costs are outlined in Table 2. Straight line depreciation was used to calculate the annual depreciation (IRS Pub. 946, 2015). Handling infrastructure is not strictly necessary for farming muskoxen. MODC combs many of their animals in milking stalls while another venture collected shed qiviut directly from the muskox pasture. However, the largest yield comes from combing calm animals so costs for a minimal handling facility were included in infrastructure estimates. Pictures and a video of combing tame muskoxen can be found on YouTube (https://www.youtube.com/watch?v=uSFeO4aN_0g). A 6.10 x 4.88 m pole barn at a cost of $12,000 is included and depreciated for an expected lifespan of 20 years. Costs for handling infrastructure (a chute and squeeze) range between $8,000-$24,000 depending on materials and configuration. An estimate of $14,000 depreciated over 7 years was used in this

budget. A truck and trailer, ATV, pull behind mowers, feed bunks and water troughs were depreciated over a span of 5 years.

A variety of fence materials have been successfully used to contain muskoxen ranging from 2 x 8 inch wooden rails, wire game fencing and both solid and open panel fencing. Bull pens are usually reinforced. LARS uses discarded highway guards or abandoned railway ties and cable. This budget assumed 183 cm 14 gauge welded wire fencing for the perimeter fence and 152.4 cm 14 gauge welded wire fencing for the interior fence. Fencing is stretched on 4x4 inch wood posts at 3.05 m intervals. Initial fencing costs, including costs of materials and construction, are calculated for the two herd size scenarios by estimating the perimeter of land requirements, 16.19/32.38 ha and minimal pen/pasture division. Initial fence construction costs have been depreciated over 15 years (Table 2). Separate annual fencing repairs are estimated in general infrastructure upkeep (Table 1).

1.3.3 Projected Revenue

Qiviut can be sold as unprocessed raw fiber or processed at a custom mill and sold as finished yarn, or a combination of both. Where the qiviut harvest was sold as a combination of raw fiber and yarn, a sales breakdown of 60% raw fiber and 40% yarn was assumed. Six different scenarios were used to estimate revenue at both herd sizes. These were factor combinations with/without livestock sales, and 100% of qiviut sold as yarn, 100% of qiviut sold as raw fiber or 40% yarn/60% raw fiber sales (Table 3).

Table 4 details the expected costs, losses, and net value per kg of qiviut in raw and yarn form. Processing into yarn by custom mills incurs additional expense as well as fiber loss. In the specification of the modelled farms, an overall fiber loss of 45% is assumed for finished yarn (based on LARS yields) and the cost of custom processing is based on current rates posted by Still River Fiber Mill (www.stillriverfibermill.com). Retail price for the yarn is $85 per 28.35 g skein (a hank or ball of yarn) or $2,998 per kg (gross value), based on the average price from a

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2015 Google Internet search. The value of yarn after accounting for processing costs, shipping, fiber losses, and transaction costs is $1,335 per harvested kg of qiviut. Raw qiviut was sold for $495 per kg or $480 after transaction costs, based on LARS 2015 sales. The processed yarn is assumed to be sold at craft fairs, farmer's markets, online, or on farm and therefore transaction costs are estimated using 2015 Etsy online venue fees of 3.5% and point of sale Square ® reader for smart phones fees of 2.75%. Raw sales to commercial merchants are assumed to have transaction costs of point of sale Square ® reader. Selling products on Etsy includes a virtual "market stall" web page that accounted for the marketing activity. Shipping and handling was charged to the buyer.

In addition to qiviut, the sale of live muskoxen could be a substantial source of revenue. MODC and LARS receive many inquiries regarding potential livestock sales. In this model it is assumed that the herd is established, with 50% of the herd being female, and 50% of those females producing calves. Half of the calves are kept for replacement and the other half (rounding up) are sold for $8,000 per head after transaction costs. The value of $8,000 was projected after interviewing industry experts and evaluating sporadic sales prices over the past thirty years (J. Blake, pers. comm. 2014, J. Rowell pers. comm. 2015). At the herd sizes of 36 and 72 muskoxen, five and ten calves were assumed sold, respectively. This estimate is considered conservative in terms of price per head and number of livestock that could potentially be sold at their reproductive parameters (J. Blake, pers. comm. 2014, J. Rowell pers. comm. 2015).

1.4 Results

The potential profitability and the break-even points of the different revenue scenarios and two scales are presented in Figure 2. Based on the projected costs and revenues, the most profitable scenario for either herd size was selling all the qiviut as yarn coupled with livestock sales. This scenario was two to four-fold more profitable than the next best option depending on the herd size. Selling a combination of yarn and raw qiviut along with livestock offered the second best potential for profitability. In the absence of selling livestock, the enterprise was profitable at either scale assuming all yarn sold at full retail price. Using a combination of 40% yarn sales and 60% raw qiviut only (no livestock sales), the enterprise broke even at a herd size of 84 muskoxen. A raw sales based operation was not projected to break even until the herd size far exceeded our theoretical maximum (126 muskoxen). Without livestock sales, variable costs were met when all of the qiviut was sold as yarn at both scales and yarn/raw at a herd size of 72 muskoxen. The results of a sensitivity analysis, where labor and feed costs were projected to increase by 10%, indicated that an increase in these keys costs would not change the profitable/not profitable status of the modelled outcomes.

Economies of scale were present in the modeled results. In addition to economies of scale for such items as depreciated costs and utilities, economies of scale for labor costs and herd health/veterinary were significant. Economies of scale accounted for a decrease in costs of approximately 26% overall, 30% in labor, and 22% in herd health, as the herd doubled in size from 36 to 72 muskoxen. The feasibility analysis also demonstrated that economic viability may be contingent on zero or low opportunity costs and favorable market conditions where yarn was sold at full retail price.

1.5 Discussion

This feasibility study models the profitability of an established farm to determine the potential economic sustainability of farming muskoxen in Fairbanks, Alaska. Using several revenue generating scenarios, the analysis indicates the possibility for economic viability, the first step in a sustainable enterprise. The modelled enterprise emphasizes the importance of value added goods such as yarn, economies of scale, and the potential of a more active livestock market. The lack of data from private enterprises limited this analysis to a broad accounting of cost variables and should be viewed in the context of the data sources.

Not addressed in this budget are startup costs, which are beyond the scope of the present study. Startup costs will vary widely depending on the assets an individual has already accrued. It should be noted that most enquiries LARS receives come from farmers interested in diversifying their current enterprise, not individuals starting with zero assets. In conjunction with startup costs, it is also important to consider the time it will take to establish a profitable herd, return on investment and the associated risk of raising non-traditional livestock. All these considerations need to be factored into an individual's economic equation.

Sources for obtaining muskoxen are currently the greatest bottleneck to a beginning enterprise. In the past, muskoxen were purchased from zoos or private game farms, sources that are more restricted today. Although livestock sales could become a large source of revenue, producers need to exercise caution in an undeveloped market with few buyers and sellers. Other non-traditional livestock markets (emus, Shetland ponies, ostriches and alpacas) have created speculative bubbles, where the sale of breeding stock becomes the main source of income, greatly elevating prices prior to their collapse (Saitone and Sexton 2007, Gillespie and Schupp 2002). The modelled muskox enterprise deliberately represented a scenario without livestock sales and demonstrated profitability selling yarn alone. In addition, we have

intentionally avoided incorporating increasing livestock value or numbers of livestock sold in the model.

While the enterprise budget broadly followed similar structures developed for bison and alpaca farming (Foulke et al., 2001; Bond, 2011), it also incorporates assumptions specific to farming muskoxen. The inclusion of fixed veterinary costs for the implementation of a proactive herd health plan is critical to mitigate health and management risks associated with raising a non-traditional species. This program is a mechanism to help the producer gain the information necessary to develop realistic production goals along with tools for monitoring the health and productivity of the animals. The consultations do not involve handling individual animals and are, therefore, a fixed cost relatively independent of herd size. Herd health further reduces labor costs by minimizing unplanned or emergency occurrences that require high labor inputs such as infirm animals, disease outbreaks, or unplanned reproductive events, while maximizing harvest yields, optimal breeding selections, and standardizing husbandry techniques. If herd health is not made a priority, there is significant risk to the investment.

Consistent labor inputs beyond those associated with traditional livestock are required to accustom calves to people and handling procedures. Animals must be amenable to being handled in order to maximize comb qiviut yield every spring and accrue possible labor economies of scale (Robertson, 2000). While handling must be consistent, no special handling beyond familiarizing calves to farm routines such as coming through the squeeze chute, weighing and moving between different pens is necessary. A previous research farm managed 120 head of muskoxen with two full time employees (P. Groves, pers. comm. 2014).

Efforts to refine the combing process are underway (J. Rowell, pers. comm. 2015). Research on qiviut and other fine fibers suggest that increases in raw yield are possible with nutritional advances, improved combing techniques and coordinated timing for combing (Ansari-Renani et al., 2013; Robertson, 2000; Boyd et al., 1996). This enterprise model assumes

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processing into yarn is done through small custom mills in the United States. Large commercial mills generally require hundreds of kilograms of fiber, making value added yarn unattainable for small farms (J. Rowell, pers. comm. 2014). Small custom mills can process fiber in batches as small as 0.45-0.91 kg (smaller than the yield of one muskox). This is an extremely important consideration for producers with small herds as it enables the producer to maintain a yearly cash flow through yarn sales.

The ability to produce value added goods coupled with Internet sales to global markets has changed the economic potential of muskox farming over the past decade. Despite the advances, market bottlenecks still affect producers; these include a lack of expertise with processing qiviut into quality yarn, and a limited amount of marketing and consumer education on qiviut qualities. These bottlenecks make it difficult for merchants to expand their qiviut distribution and limit their choice when processing their fiber. The model, as presented, depends on the producer selling all the yarn every year. This may become increasingly more difficult as the market expands.

The principal competition for farmed qiviut is qiviut from wild sources. The bulk of qiviut on the market is harvested from wild muskoxen whose abundance fluctuates. The volatility of wild qiviut supply, in conjunction with the limited amount of farmed qiviut has created an unpredictable availability of raw fiber. To ensure supply, many commercial enterprises stockpile fiber from multiple sources: farmed, collected, or plucked from hides. Due to this limited supply (from all available sources) and the size of the market, there is no price or labeling differentiation between wild and farmed qiviut at any point in the marketing channel, from raw to finished garment. The price for raw, wild qiviut is approximately \$220-290 kg^{-1} depending on the condition and whether it is on a hide (personal communication with buyers). The current price for raw farmed qiviut is approximately \$495 kg^{-1}. While wild raw qiviut is a close substitute good, the condition and supply of farmed qiviut is more consistent and commands a price premium.

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The large price differential reflects the importance of access to a consistent supply in a tight market.

Historically, the price of raw farmed qiviut was determined by the initial non-profit farm in a relatively arbitrary manner due to the lack of an established qiviut market (Watson and Groves, 1989). Currently, the price of farmed raw qiviut, while higher than wild qiviut, is still not high enough to cover production costs. The lack of market differentiation and consumer familiarity between wild and farmed sources may have prevented farmed qiviut from capturing the full value premiums associated with farm production once the qiviut market became more established. Farmed qiviut may be instrumental in the growth of the qiviut market. It has the potential to enhance the sustainability of the industry for both the subsistence communities that harvest wild qiviut as well as the agricultural community by ensuring a consistent supply and maintaining or increasing a market presence. Developing farming efforts in synchrony with wild harvest could alleviate commercial pressure on wild populations and stabilize market supply.

Regardless of source, the processed qiviut is marketed into two general sales channels: smaller retail stores, craft fairs, or farmer's markets selling yarn, roving, and small knitted items, and luxury boutique establishments selling fine knitted and woven garments. Qiviut yarns are often blended with other fibers such as cashmere, silk, merino wool, and bamboo. An Internet search (May 2015) found the price of a 28 g 100% qiviut skein of yarn averages $85 (range $60-120) and small finished goods such as hats, scarves, and cowls range from $150-400. Large finished garments, such as sweaters, blankets, and woven cloth made into designer suits, cost $600 to $25,000 (Kissel, 2009). The qiviut market would seem to have substantial potential for growth; consumers spend $80 billion on wool garments globally (Swan, 2013). Furthermore, the top 5% of consumers account for 38% of spending on wool apparel (Swan, 2013). Luxury apparel is the fastest growing segment of the fine fiber industry (Swan, 2013). The increasing popularity of fine fibers in luxury markets, coupled with the increased market demand for

sustainable, organic, and heirloom products could enable qiviut producers to use marketing to develop a larger niche for qiviut sales.

This analysis did not evaluate the revenue potential of finished garments for the modelled farm. Possible market expansions could include elite outdoor sportswear applications, expanded luxury markets and greater use in fiber blends for commercial garment manufacturing. In addition to expanded uses for qiviut, other sources of revenue could include livestock workshops, head mounts, horn sales, and agrotourism. Muskoxen have value as a subsistence food animal but no commercial market for muskox meat has been developed and hence meat sales and hunt farms were not considered in this model.

Both MODC and LARS run successful agrotourism enterprises as a substantial source of revenue. While the agrotourism potential was not evaluated in the context of this feasibility analysis, the presence of these enterprises is a useful indicator of economic importance beyond the consumptive value. The social component of sustainability is well represented by the ticket sales and community interest in viewing the farm and livestock.

Economic value is often thought of as a measure of monetary worth, but the total economic value of an enterprise consists of social and environmental benefits not directly captured by the market. These non-monetary values, such as the value of environmental services are also critical considerations to the sustainability of farming muskoxen and are not reflected in this enterprise budget. Research suggests that grazing in circumpolar regions is an important part of nutrient cycling and can improve the condition and productivity of circumpolar rangeland if properly managed (Olofsson et al., 2001; McKendrick et al., 1980). Social value to the community may include livestock diversity, cultural significance, and the existence of sustainable agriculture for circumpolar climates. While it is a challenge for producers to capture the non-market environmental value beyond the cost savings, niche product marketing

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associated with conservation, environmental sustainability and ecosystem stewardship could impact the value of qiviut and command a price premium in luxury and eco-markets.

1.6 Conclusion

The model we present is conceptual and designed to look at the economic feasibility of an established muskox farm within the context of a sustainable enterprise. Under a number of different scenarios muskox farming can be economically viable within the limitations outlined in this study. The results indicated that economies scale, the sale of value added goods, and a lack of opportunity cost contributed to enterprise profitability. The study incorporated broad, primary costs associated with raising a non-traditional species. Startup costs, which could be substantial and specific details of land costs, interest rates or sources of muskoxen for farming, were not addressed. These are all significant considerations and any one of them could change the profitability equation.

However, creative agricultural endeavors in harmony with the environment have the greatest chance for success and sustainability in marginal ecosystems. The findings from this exercise suggest that using an indigenous species such as muskoxen to harvest renewable landscape resources in marginal habitats, enhance ecosystem services in Alaskan pastures, and exploit niche fiber markets, could promote a unique and sustainable agricultural model for the future.

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1.8 Tables

Table 1.1 Estimated operating costs for a hypothetical muskox farm in Alaska at two herd sizes, 36 and 72 head

| Operating expenses* | Price per unit | Operating cost on a herd basis ($) | |
		Herd size 36	Herd size 72
Feed			
Hay – 363 kg bales	$190	15,960.00	31,730.00
Grain ration – 22.68 kg bag	$20.50	9,000.00	18,000.00
Hired labor			
1040 hours	$15/hr	15,600.00	-----
1240 hours	$15/hr	----	18,600.00
Summer – 320 hours	$10/hr	----	3,200.00
Pay roll tax (% of labor costs)	26%	4,056.00	5,668.00
Veterinary care			
Herd health consultation	$200/hr	800.00	800.00
Emergency care	$200/hr	540.00	1,080.00
Vaccinations	$1.30/dose	118.80	237.60
Qiviut profile test	$9.50/sample	342.00	684.00
Misc supplies	estimate	1,000.00	1,500.00
Property taxes ($617.50/ha)	1.58% mill rate	158.00	316.00
Insurance	insurance quote	3,500.00	4,500.00
Interest on capital**	7%	5,062.55	7,649.81

Table 1.1 continued

Operating expenses*	Price per unit	Operating cost on a herd basis ($)	
		Herd size 36	Herd size 72
Internet/phone (per month)	$100	1,200.00	1,200.00
Electricity/water/heat (per month)	$250	3,000.00	3,000.00
Fence (repairs per 30.5m)	$270	270.00	540.00
Vehicle and equipment (fuel/repair)	estimate	3,500.00	3,500.00
Total Operating Costs		**$64,107.35**	**$102,205.41**

* Assumed that the land is 100% operator owned and therefore operating expenses do not include a cost for a land purchased loan

** Percentage of total costs (operating + depreciated)

Table 1.2 Estimated depreciated costs for a hypothetical muskox farm in Alaska at two herd sizes, 36 and 72 head

| Depreciation Costs* | Lifespan (yr) | Value per Unit ($) | | Total ($) Depreciated Value | Annual Cost per Muskox Herd ($) | |
		New market value per unit	Residual** value		Herd size 36	Herd size 72
Pole barn	25	12,000.00	0.00	12,000.00	480.00	480.00
Squeeze/chute	10	14,000.00	1,000.00	13,000.00	1,300.00	1,300.00
Mower	10	1,000.00	100.00	900.00	90.00	90.00
Truck and trailer	6	50,000.00	3,000.00	47,000.00	7,833.33	7,833.33
ATV	10	7,500.00	500.00	7,000.00	700.00	700.00
Slanted feed bunks -3.7 m	10	800.00	0.00	4,800/9,600***	480.00	960.00
Poly water tank – 435.3 l	10	80.00	0.00	480/960***	48.00	96.00
Fence – 1.8 m on 3 m spans	10	250 per 30.5 m	0.00	23,460/32,680***	2,346.00	3,268.00
Total					$13,277.33	$14,727.33

*Straight line depreciation [(new market value – residual value)/lifespan]

**Residual value (or salvage value) – The remaining value of the asset after it has been fully depreciated over its expected lifespan

***Depreciated cost that varies over the 36/72 muskox herd size

Table 1.3 Income potential from the modelled revenue streams

	Qiviut produced (kg/yr)	Livestock Available (for sale/yr)	Qiviut and Livestock Revenue		
			Livestock revenue ($8,000/head)	All qiviut sold raw ($481/kg)	All qiviut sold as yarn ($1,335/kg)
Herd size 36	63.31	5	40,000	30,452	84,518
Herd size 72	126.61	10	80,000	60,899	169 024

Table 1.4 Processing and transaction costs, percentage of fiber loss in processing, and expected revenue from 1 kg of combed qiviut sold as raw fiber or yarn

Qiviut	Processing Loss (%)	Processing Cost ($)	Transaction cost (% of sale value)	Revenue after losses/costs per kg combed qiviut ($)
Yarn	45	372.30	6.25	1,335.00
Raw	0	0.00	2.75	481.00

1.9 Figures

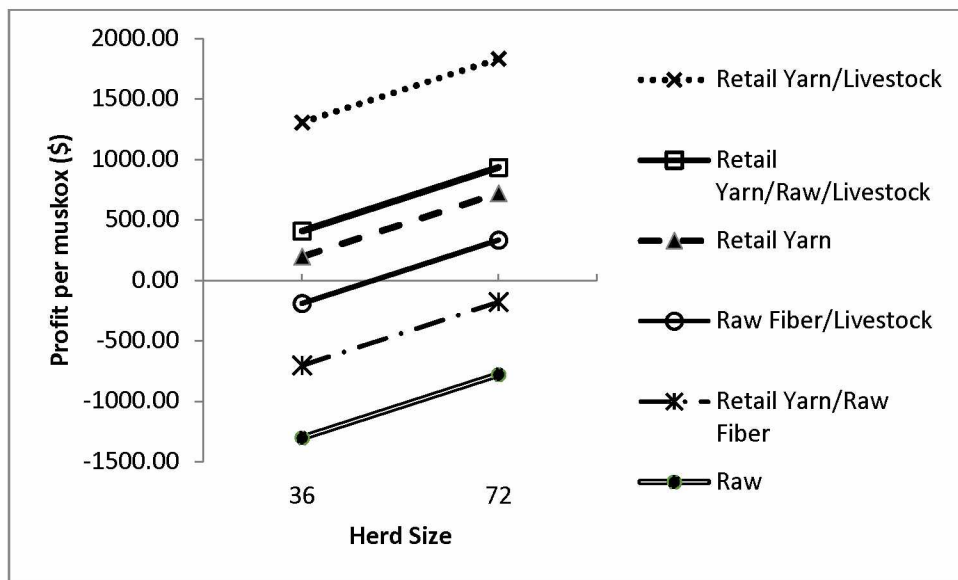*Figure 1.1 An adult female muskox being combed at LARS*

Figure 1.2 Potential profit (total revenue – total cost) per head from six different revenue stream combinations of qiviut yarn, raw qiviut, and livestock/no livestock sales at two farm scales, 36 and 72 muskoxen. The breakeven herd size for each modelled

Chapter 2 Sustainable livestock production in sub-arctic Alaska: Plant and soil responses to simulated intensive grazing[1]

2.1 Abstract

Pasture management for livestock production under sub-arctic conditions is a challenge. The interior of Alaska is characterized by an extremely cold and dry climate, short growing season, slow residue decomposition rates and undeveloped soils that are vulnerable to compaction and erosion. While commercial livestock production is limited, Alaska is home to some of the largest herds of wild ungulates in the United States; a testament to the suitability of the region to grazing. Currently, unmanaged livestock grazing has resulted in a heterogeneous pattern of use; with animal feeding preferences creating patches of both over- and under-utilization, and degradation. Pasture resource optimization and ecosystem health are key concerns for Alaskan farmers.

The goal of this research was to evaluate the response of sub-arctic pastures to an intensively managed rotational grazing (IMRG) and examine the role of grazing mechanisms on pasture productivity and ecosystem services. To evaluate the impacts of IMRG, a full factorial experiment of simulated trampling (T), muskox (*Ovibos moschatus*) dung/urine deposition (M), and herbivory (forage clipping) (H), mimicking IMRG timing and intensity, was conducted at the Robert G. White Large Animal Research Station, University of Alaska, Fairbanks. The simulations were conducted on 96-1 m^2 plots in two established pastures (hilltop and hill bottom) with different soil types and dominant plant species, over the 2014 and 2015 grazing seasons. Treatment effects on plant biomass, percentage of bare ground, physical soil characteristics, and soil biota were measured from one and two years of treatment applications to evaluate the

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potential suitability of IMRG for livestock farms in interior Alaska and provide insight into the role of grazing disturbance mechanisms on sub-arctic soil and forage yield.

Treatment impacted plant biomass on all treatment groups (p<0.05). Treatments MH and MTH had a positive impact in both pastures over two years of treatment application (p<0.05). Both 1 yr pastures had the most positive treatment effect from MH and H (p<0.05). Treatments T and MT had a negative impact on biomass production in both pastures and years (p<0.05). The TH treatment had a negative impact on both 2 yr pastures sites (p<0.05). After two years there was no difference in bare ground estimates in either pasture (p>0.16) when treatments were compared to controls but in the hilltop, T reduced bare ground compared to TH, and in the hill bottom, MT reduced it compared to TH and H (p<0.05).

Treatment impacted soil parameters in both pastures. The hilltop pasture after two years showed the greatest impact; MT had 93% more total water soluble nitrogen (N) and 287% more H3A extracted inorganic N than control (p<0.05), MTH had 46% more organic phosphorus (P) than control (p=0.05), and MTH and MT improved the Haney soil health score by 69% over control (p≤0.03). In the hill bottom pasture, MTH had 28.5% more total water soluble N than control (p<0.05), and MT had an increased arbuscular myccorhizal biomass (p=0.04) compared to H. While treatments H, T, and TH often had the lowest soil parameter measurements in both pastures, in no case did they significantly differ from the control.

2.2 Introduction

Many ecosystems in Alaska are well suited to grazing. The North American subarctic supports some of the largest wild herds of grazing ungulates on the continent yet livestock production in Alaska remains relatively undeveloped. In 2012, it was estimated that there were less than 17,000 head of livestock in the state. Despite the enormous size of Alaska, the land currently in pasture is small in size compared to other states, less than 299,000 ha (Dinkel, 2012). This constraint of space, along with the extreme climatic conditions, a short growing season, expensive imported farm inputs, and competition from other markets, makes maximizing land resources and understanding the potential impacts of grazing livestock in the subarctic environment crucial. With a growing global population and increased prosperity in countries such as China and India, the demand for livestock products is expected to increase exponentially (Pica-Ciamarra *et al.*, 2014). This increase in demand coupled with the impacts of climate change and increased pressure on natural resources, makes the question of efficient and sustainable livestock grazing critical (Joyce, 2013).

Grazing can be the largest biotic disturbance on rangeland ecosystems (Wang, 2006). Ungulates impact the ecosystem via three mechanisms: waste deposition, trampling, and herbivory. These mechanisms affect plant and soil biota, nutrient cycling, hydrological cycling, and soil physical properties in a complex web of interactions (Coughenour, 1985; Teague *et al.*, 2011). As with other disturbances, grazing can have positive or negative impacts on the ecosystem depending on the timing, frequency, and intensity (Wang *et al.*, 2006). Grazing management regimes are designed to control the impact and spatial distribution of this disturbance, and to influence the impacts and outcomes of grazing livestock.

Grazing regimes vary from unfettered access to large areas over the course of years to the daily rotation of a herd into different paddocks. Grazing is spatially heterogeneous due, in

large part, to livestock preference for certain plant species, preference for new growth, ease of access, and proximity to water (Briske *et al.*, 2008). When livestock have unlimited access to the pasture area over the course of the growing season, as is common in continuous grazing regimes, patches of the landscape are over and underutilized where new, preferred plant growth is grazed repeatedly and mature plant stands are not consumed (Loeser *et al.*, 2007; Barnes *et al.*, 2008). This heterogeneous pattern creates areas that are subject to deleterious grazing pressure even under light stocking rates for the paddock size (Barnes *et al.*, 2008; Teague *et al.*, 2011). These over-utilized patches can spiral into a positive feedback loop where desirable plant communities, soil structure, soil biota, nutrient cycling and hydrological function are compromised and the area deteriorates (Norton, 1998; Teague *et al.*, 2011).

Wild ungulates historically grazed in vast herds across rangelands, utilizing any available forage but constantly moving due to factors such as predation and water availability (Savory, 1983). Many environments evolved with large herds of grazing ungulates and these herds played a vital role in ecosystem function. Some practitioners and researchers have demonstrated that domesticated livestock can be used to fill that role with intensively managed rotational grazing (IMRG) (Savory, 1983; Norton, 1998; Jacobo, 2006; Teague *et al.*, 2011). IMRG proposes to improve pasture usage and ecosystem function by controlling the intensity and frequency of grazing disturbance. It is used to mimic the short but intense grazing periods of wild, migratory ungulates. The practitioners of IMRG describe the successful use of stocking densities up to twice what is possible using a continuous grazing regime, while restoring and maintaining healthy ecosystem function (Barnes *et al.*, 2008).

IMRG models the grazing patterns of wild ungulates by stocking sections of the land at a high density and moving the herd from section to section (or paddock) at varying rates throughout the growing season, based on forage utilization and plant growth rates rather than rigid calendar schedules (Savory, 1983, Savory and Butterfield, 1999; Teague *et al.*, 2004;

Teague *et al.*, 2011). This type of grazing management has been shown to improve spatial distribution of grazing pressure where an increased sense of competition encourages livestock to eat all the forage provided, effectively increasing the available amount of forage in a given area and preventing over consumption of desirable plant species (Teague *et al.*, 2011; Barnes *et al.*, 2008), which otherwise could lead to increasing dominance of less-desirable plant species. IMRG encourages new growth and tillering in some plant species, providing more palatable forage and increased primary productivity (Coughenour *et al.*, 1985).

Constant livestock movement prevents over grazing and over trampling certain spots and more evenly distributes dung and urine (Savory, 1983). Partially decomposed organic matter is incorporated into the soil profile from brief but intense trampling. Increased organic matter and improved incorporation is thought to increase soil biota activity and encourage decomposition, thus enhancing nutrient cycling (Savory, 1983; Donkor *et al.*, 2002; Teague *et al.*, 2011). The incorporated organic matter will lend to the resilience and stability of soil structure. This increased stability in soil structure could mitigate adverse effects from trampling and soil compaction (Teague *et al.*, 2011; Briske *et al.*, 2008; Barnes *et al.*, 2008). Academic research has had mixed conclusions about the efficacy of IMRG and has not conclusively demonstrated the outcomes of these ecological assumptions (Teague *et al.*, 2013; Briske *et al.*, 2008; Donkor *et al.*, 2002).

Several studies have demonstrated that subarctic ecosystems benefit from intensive grazing pressure because of more rapid nutrient cycling from ungulate digestion. Grazing research has documented increased primary productivity due to heavy grazing by muskoxen on a sub-arctic farm and in the high arctic wilds (McKendrick *et al.*, 1980; McKendrick 1981). Olofsson et al. measured increased primary productivity and nitrogen cycling as a result of heavy reindeer grazing (Olofsson *et al.*, 2001). A simulated study in northern Sweden detailed an increased abundance of soil bacteria and bacteria feeding nematodes only in plots that

received trampling and fertilization, compared to plots that received fertilization alone, demonstrating the impact of trampling on soil biota in subarctic soils (Sorensen, 2009). These studies suggest that IMRG systems may have the potential to improve pasture ecosystem function while increasing available forage in the subarctic environment.

The challenges that Alaskan livestock producers face are such that an increased carrying capacity, reduced dependence on imported fertilizers, and need to restore and protect ecosystem function would be key aspects in developing environmentally and economically sustainable grazing practices for the region. Soils in the Alaskan interior are extremely sensitive to compaction (NRCS, 2016). They are characterized by poorly developed structure due in large part to the cold temperature, low precipitation regime, and resulting slow decomposition rates (NRCS, 2016). In the spring, the soil is frozen and impermeable long after the snow has thawed and runoff, carry away many water-soluble nutrients with it. It is unknown whether IMRG systems would provide net benefit or harm to pasture health due to increased grazing pressure (Warren et al., 1986; Donkor et al., 2002). The knowledge gap addressed in this research is whether the theories that underpin IMRG will prove true for producers, in the unique Alaskan subarctic environment.

The overall objective of this research was to evaluate the separate grazing mechanisms in the context of an IMRG regime in the interior of Alaska to better understand grazing management. The specific objectives of this research are:

1) Simulated IMRG disturbance treatments will affect plant biomass (forage) production and percentage of bare ground.

2) Grazing treatments will impact soil physical and chemical parameters.

3) Grazing treatments will affect the abundance and activity of the soil microbial community.

For this study, we employed simulated grazing techniques to evaluate above and below ground response to an IMRG regime and to gain insight on the role of grazing disturbance mechanisms on sub-arctic soil and plant health (Kohler *et al.*, 2005; Sorensen *et al.*, 2009). A full factorial experiment of simulated trampling, muskox dung/urine deposition, and forage clipping, mimicking IMRG timing and intensity, was conducted in Fairbanks, Alaska. The outcome of this research provides a twofold benefit; it evaluates site-specific responses to IMRG and provides insight into the role of grazing disturbance mechanisms on sub-arctic soil and plant health. It is also a first step in addressing the development of sustainable grazing practices for Alaska.

2.2 Materials and Methods

2.2.1 Research Site

This research was conducted at the Robert G. White Large Animal Research Station, with an elevation of 210 MASL, at the University of Alaska, Fairbanks, in central Alaska, USA (64.878, -147.866). The Fairbanks area has a mean annual temperature of -2.5° C, 27.5 cm mean annual precipitation, and 80 to 120 frost-free days (Alaska Climate Research Center). LARS is a 54.23 ha research farm facility that is sown with Smooth bromegrass (*Bromis inermis), Kentucky bluegrass (Poa pratensis)*, and Red fescue (*Festuca rubra)*. Soils at the research site are a silt loam with less than 10% clay content and poorly incorporated organic material. The site has been continuously grazed by muskoxen (*Ovibos moschatus)* and reindeer (*Rangifer tarandus)* since 1980. These animals were excluded from the area for the duration of the study.

The trials were carried out during the 2014 and 2015 growing season (approximately 110 days for each year). Temperature (0.32°C in 2014, 0.1°C in 2015) and precipitation (18.97

cm in 2014, 8.41 cm in 2015) was above average in both years, compared to 30 year summer averages (Table 1). The experiment was conducted in two, south facing pastures with different soil types, moisture regimes, and dominant plant species (Fig. 1). The hilltop pasture was dominated by Kentucky bluegrass and had well-drained, Fairbanks silt loam with loess parent material (NRCS, 2016). The hilltop pasture was the drier (approx. 10% less soil moisture than the hill bottom) and more degraded of the two sites (28% bare ground compared to 11% on the hill bottom site pretreatment). The hill bottom pasture was predominantly Smooth brome grass and Common quackgrass *(Elymus repens)*, and had Minto silt loam with a colluvium and loess parent material (NRCS, 2016). The hill bottom site was on average 2.85°C cooler (4.76°C cooler in June) on the soil surface and 1.63°C cooler, 5 cm below ground. Both soils types are described as a coarse-silty, mixed, super active, Eutrocryepts, to a depth of more than 203 cm based on US Soil Taxonomy (NRCS, 2016). While both soils share similar physical and chemical characteristics, the Minto silt loam has a slightly slower drainage rate, deeper surface organic layer, and shallower depth to the water table (NRCS, 2016).

2.2.2 Research Design

Experimental design consisted of fully factorial combinations of grazing mechanisms; simulated herbivory (H), manure and urine application (M), and trampling (T) using a completely randomized block design. A control plot (no treatment) was present in each block. This factorial combination gave eight treatment types including the control (C), they were MTH, MT, MH, M, TH, T, H, and C. In each, the hilltop and hill bottom sites, three blocks of eight, 1 m^2 (0.5 m x 2 m) plots, were established in 2014 and treated over two years to study treatment impact from one year application (2014) and cumulative treatment impact over two years (2015). A second set of treatments was established in both locations in 2015, to study one year impact of treatment. In combination with 2014, weather impact on treatment effect can be evaluated. This

one year experiment in 2015 was set up within 3 m of the original block sites to compare results after one year of application. The blocks were established in the pastures along east-west transects 1 m apart, with a 1 m buffer between plots. All plots were in full sun with southern aspect. All plots were analyzed for soil chemical and biological parameters, percentage of bare ground directly prior to experiment implementation to ensure no existing significant differences among plots. The experiment assumed normal pasture management and control plots represented a pasture at rest. In keeping with this assumption all plots received annual spring inorganic fertilizer applications of 10-10-10 NPK at a rate of 135 kg per ha. All plots were clipped at the end of the year.

Treatments were devised to replicate grazing impact of IMRG of muskoxen, an indigenous livestock species in Alaska. Adult muskoxen weigh 200-300 kg and thrive in sub-arctic conditions. Treatments were initiated June 2-4, 2014, as soon as vegetation had become established and grass tillers had reached third leaf stage (Manske, 2003). When plants reached an average height of 20-25 cm, treatments were reapplied to simulate a grazing event. IMRG regimes emphasize that grazing rotations must be initiated in response to plant growth, not according to set calendar periods, resulting in variable time periods between treatment applications and variable times between treatment of the hilltop and hill bottom sites (Table 2).

Treatments were applied to each site in the following order: herbivory, manure and urine deposition, and trampling. Herbivory (H) was simulated by manually cutting vegetation to an average residual height of 8-10 cm per treatment application leaving the recommended 30-50% foliage for plant recovery (Kohler *et al.*, 2005). Only plant material that stood above the 8 cm was clipped. If plant material was long but was trampled onto the ground, it was not lifted to be clipped. The manure/urine application (M) consisted of fresh dung (6 g total N kg^{-1} dung) that was collected from LARS muskoxen and urine was simulated by mixing 5.15 g of urea per 1 L water (Persson, 2003). Each plot that was scheduled to receive dung/urine applications

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received 3 L of dung and 1.5 L of urea water (35.5 kg^{-1} ha total N) spread over the 1 m^2 (Kohler

et al., 2005). Trampling (T) was simulated by rolling a 70 kg weighted tractor tire across the

entire plot representing a mean pressure of 7000 kg m^{-2} and repeated 6 times (Kohler *et al.*,

2005; Sorensen *et al.*, 2009). These trampling plots were stabbed 12 times with a shovel to

mimic hoof cutting action in the soil and plant material. Plots that had no manure/urine

applications (T and TH) were trampled first, followed by the trampling plots that received

manure and simulated urine (MTH, MT) to prevent cross contamination. The trampling

apparatus and shovel were then washed thoroughly for future treatment applications.

2.2.3 Above Ground Parameters

Plant biomass which was clipped in the herbivory treatments were collected and dried

for 24 hr at 65° C to obtain a dry weight measurement. Hilltop plots were clipped four times in

both 2014 and 2015 while hill bottom plots were clipped five times throughout the growing

season. Plots that did not receive the H treatment were clipped once at the end of the season

(Table 2). All treatment dry weight measurements in a plot were added to obtain an annual

forage yield. The plots established in 2014 were treated and measured in the 2014 (first year),

2015 (second year) growing seasons. The plots established in 2015 were treated and measured

in the 2015 (first year) growing season. The experimental treatments ended in September, 2015

and the plots were left undisturbed until they were all clipped once in July 2016 as a post hoc

measurement.

Change in the percent bare ground was measured in plots that were treated for two

years, using a plastic frame, at the beginning and end of the experiment. The 1 yr groups were

not measured due to the short time interval.

2.2.4 Soil Sampling

All soil sampling was conducted at the beginning and end of the experiment; June 2015 and Sept. 2016 for the two-year application, and June and Sept. 2015 for the one-year application. Samples were collected on each site (hilltop/hill bottom) on the same day. Baseline soil samples were taken immediately before initial treatment application to establish baseline measurements. Samples were taken to measure treatment effects on soil chemical properties, microbial communities, and compaction. Soil samples were collected to measure soil respiration (Solvita® CO_2 burst test), organic matter content, soluble soil nutrient content, soluble organic C:N ratios, soil health calculation using a Haney Soil Health Test. The soil health calculation ((Solvita CO_2/Organic C:N)+(Water-extractable Organic C/100)+(Water-extractable Organic N/10)) is an index combining several properties that contribute to the biological wellbeing of the soil for an alternative measure of soil health (Haney, 2012). Microbial biomass and community changes were measured using a phospholipid fatty acid analysis (PLFA) (Frostegard *et al.*, 2010). Each plot sample consisted of 6-10 cm deep soil cores which were pooled and frozen within 4 hr. Samples were sent to Ward Laboratories, Kearney, NE for Haney Soil Health Test and PLFA analysis.

For the Haney Soil Health test, the soil samples were air dried at 50°C for at least 24 hours and sieved. The sample was divided into three quantities; 40 g used for the CO_2 analysis, 4 g extracted with DI (deionized) water, and 4 g extracted using the H3A extractant to mimic the acidic root exudates in soil (Gundersen, 2016). The 40 g sample was rewetted and incubated for 24 hr at 25°C. During the incubation period, CO_2 carbon from samples was analyzed in a Solvita® digital reader (Woods End Laboratories, Inc. Mount Vernon ME, USA). The water and H3A extracts were analyzed for NO_3^-, NH_4^+, and PO_4^{3-} using a Lachat 8000 flow injection analyzer (Lachat Instruments, CO, USA). The water extract was further analyzed for organic

carbon and total nitrogen in a Teledyne-Tekmar torch C:N analyzer (Teledyne Tekmar, OH, USA), while the H3A extract was analyzed for Al, Fe, P, Ca, and K with a Thermo Scientific ICP-OES (Thermo Fischer Scientific, MA, USA) (Gundersen, 2016).

The phospholipid fatty acids (PLFA) found in the cells of the microorganisms were analyzed in each soil sample to estimate functional microorganism group abundance and changes in the microbial community in response to the simulated grazing treatments. The PLFA was conducted at Ward Laboratories using the methods described in Hamel et al. (2006) as follows: a 2 g air dried sample from each plot was shaken with 9.5 ml of dichloromethane (DMC), methanol (MeOH), and citrate buffer (1:2:0.8 v/v) for 1 hr. After that 2.5 ml DMC and 10 ml of a saturated KCl solution was added and shaken at 240 rpm for 5 min. Samples were then centrifuged for 10 min at 3000 rev min^{-1} and then the organic fraction was collected into vials. The organic fractions were then dried under N_2 gas at 37°C and then dissolved in 2 ml of DCM. Silica gel columns were used for the lipid class separation. Sequential leaching with acetone was used to elute the neutral, glycol, and phospholipid factions (Hamel et al., 2006). Only phospholipids were collected. The resulting samples are analyzed using an Agilent 7890A GC with a 7693 Autosampler (Agilent Technologies, CA, USA).

Additional samples (0-15 cm) were taken to analyze changes to the soil's physical properties. Changes to the soil bulk density and penetration resistance were calculated to measure soil compaction before and after the study. Bulk density was measured using a bulk density soil core sampler (117.81 cm^3) to remove one core per plot. Cores were dried in 105°C oven for 24 h. Bulk density was calculated using mass of dry soil sample (g) divided by the volume of the core sampler cylinder. Penetration resistance was measured using an Eijkelkamp hand penetrometer (Eijkelkamp, Geisbeek, Netherlands). The device was inserted to a depth of 15 cm four times per plot to obtain a mean measurement of the pressure required (resistance) to insert the cone and rod into the soil (Duiker, 2002).

2.2.5 Statistics

Treatment effects on soil chemical, biological, and physical properties were analyzed using Sigma Plot 13.0 (Systat Software Inc., IL, USA). Our level of significance was $p \leq 0.05$. However, $p \leq 0.1$ but ≥ 0.05 was considered evidence of an emerging trend.

Means of the soil assays and forage biomass measurements for each of the eight treatment types from the three replicated blocks in the group were analyzed using a one way analyses of variance (ANOVA) for each of the soil parameters and plant biomass measurements. All tests that passed the Shapiro-Wilk normality test, the Brown-Forsythe equal variance test, and showed a significance ($p < 0.05$), received the post hoc multiple pairwise comparisons and multiple comparisons vs. control using the Holme-Sidak method. All data that failed the Shapiro-Wilk normality test ($p < 0.05$) were analyzed using Kruskal-Wallis One Way Analysis of Variance on Ranks. Measurements not statistically different from one another were reported as an average of the group.

The 1 yr forage biomass results from 2014 and 2015 were analyzed for the inter-year effect using a split plot analysis (Table 3). Year did not affect biomass in the hilltop pasture ($F=8.00$, $p<0.11$) (Table 3), therefore the 1 yr hilltop (2014 and 2015) forage yield measurements were combined and analyzed together. A log 10 transformation was used for this non normal data. There was a year effect ($F=208.74$, $p=0.01$) in the hill bottom pasture, therefore 1 yr treatment data from 2014 and 2015 were analyzed separately (Table 3).

2.3 Results

2.3.1 Impact on Above Ground Parameters

H_0: The IMRG application of simulated grazing mechanisms (herbivory, trampling, manure/urine application) singly or in combination, has no effect on forage biomass production or the amount of bare ground present.

We reject the null hypothesis. Treatment impacted biomass production on all treatment groups in pairwise comparisons and when compared to control ($p<0.05$). Treatments MH and MTH had a positive impact in both pastures over two-years of treatment application ($p<0.05$). Both 1 yr pastures had the most positive treatment effect from MH and H ($p<0.05$). Treatments T and MT had a negative impact on biomass production in both pastures and years ($p<0.05$). The TH treatment had a negative impact on both 2 yr pastures sites ($p<0.05$). A trend began to emerge in 2015, where both 2 yr pasture sites produced a mean 29.5% more DW forage compared to the 1 yr treatment groups ($p=0.08$).

One year treatment effects: 2014 Forage biomass production
Hilltop – (2014, 2015 combined)

After 1 yr of treatment, all treatments but TH produced more DW forage than the T and MT ($p\leq0.02$). The MH treatment also out produced DW forage production of TH ($p=0.03$) (Table 4).

Hill bottom – 2014

The MTH treatment had the highest forage production after 1 yr (2014), out producing MT ($p=0.04$) (Kruskal-Wallis ANOVA on Ranks) (Table 5).

Hill bottom – 2015

More plant biomass was measured in MH and MTH than all other treatments, including control (p<0.04) (Table 5). These two treatments produced approximately 30% more DW forage compared to control. Similar to all other sites, trampling (T and MT) had a negative impact on the amount of clipped plant biomass compared to all other treatment types (p<0.001) (Table 5).

Two-year treatment effects: 2015 Forage biomass production
Hilltop

Manure, alone and in combination (MH, MTH, and M) produced the most DW forage, exceeding T, MT, and TH treatments (p≤0.01) (Table 4). In addition herbivory alone (H) increased forage yield over T and MT treatments (p≤0.01). The T, and MT treatments had a negative impact on forage yield (74-79% less), compared to control (p<0.02) (Table 4).

Hill bottom

More plant biomass was produced in MTH, MH, H, and M treatments compared to T, MT, TH, and control plots (p≤0.001) (Table 5). Forage production in the highest producing plots was approximately 40% greater than control. In addition to these effects, TH and control plots had higher forage production than T and MT (p<0.001). Like the 2 yr hilltop pasture, T and MT treatments had a negative (p<0.001) impact on forage production, producing approximately 67% less biomass than the control (Table 5).

Percent bare ground
The overall trend was a decrease in percent bare ground in all treatments; control plots reduced bare ground by 30% (hilltop) and 6% (hill bottom) over the course of the study. After 2 yr there was no difference in bare ground estimates in either pasture (p>0.16) when treatments were compared to controls. In the hilltop group, T had the greatest impact on the reduction of bare ground which was an improvement (p=0.04) when compared to TH. The manure and trampling (MT) had the largest effect in the hill bottom pasture, reducing bare ground by 18%.

This was different when compared to TH and H, which increased the amount of bare ground (6% and 5% respectively) (p=0.05).

2.3.2 Impact on Soil Properties

H$_0$: The IMRG application of simulated grazing mechanisms (herbivory, trampling, dung/urine application) singly or in combination, has no effect on soil physical and chemical properties.

We reject the null hypothesis. Treatment impacted soil properties on all treatment groups in pairwise comparisons and/or compared to control (p<0.05). The MT and MTH treatments had the greatest impact on soil over 2 yr treatment in both pastures with trends following apparent after 1 yr of treatment. Both pastures sites treated for 2 yr had a significant, positive effect in the total amount of water soluble nitrogen (N) and H3A extracted inorganic N over the control (p<0.05). While treatments H, T, and TH often had the lowest measurements, in no case did they significantly differ from the control. While not significant, similar trends (p<0.1) began to emerge after 1 yr of treatment.

Total water soluble nitrogen

Hilltop

After 1 yr a trend began to emerge where MT had the highest levels of water soluble total N differing from T (p=0.09) and had 39% higher total water soluble N than the control. After 2 yr there was 93% more total water soluble N in MT than control (Fig. 2) (p=0.03).

Hill bottom

After 1 yr, MTH had the highest measurement of total N, tended to differ (p=0.07) from TH. After 2 yr treatment, significantly higher levels (p<0.02) were found in MTH and MT compared to T and H. The MTH treatment also significantly differed from control with 28.5% more water soluble N (p=0.05) (Fig. 3).

H3A extracted inorganic nitrogen (NH_4^+ and NO_3^-)

Hilltop

After 1 yr of treatment a trend for increasing inorganic N emerged in MT where it differed most from H (p=0.07) and had 105% more inorganic N than control (p<0.1). This trend became significant after the second year, MT was significantly higher (MT vs C; p=0.02; Kruskal-Wallis) representing a 287% increase over control (Fig. 2). Differing from the total inorganic N results, nitrate (NO_3^-) were highest in MTH compared to control (p=0.01) and represented a 444% increase over control.

Hill bottom

After one year of treatment, the difference in the inorganic N between MTH and TH followed a similar trend to the hilltop (p=0.06). The MTH treatment had 99% more inorganic N than control plots (p<0.1) while nitrate was 200% higher in MTH over control (p=0.08). After two years of treatment, MTH differed (p=0.02; Kruskal-Wallis) from T (Fig. 3). The sample mean of MTH treatments was 8.6 ppm compared to 4.2 ppm in control. While this represents a 106% difference, the high variability and non-parametric analysis prevented the interpretation of the data as significant for the population (Fig. 3). Nitrate was significantly higher (p=0.02) in MTH plots compared to T.

Organic Phosphorus

Only the 2 yr hilltop pasture showed any treatment effect in the amount of phosphorus (P). The MTH treatment (19.57 ± 1.98 mg/kg) had the highest values, differing significantly (p=0.04) from the lowest values in T (13.07 ± 0.15 mg/kg). The MTH treatment also had 46% more organic P compared to control (13.43 ± 0.58 mg/kg) (p=0.05).

Haney soil health calculation

Hilltop

Adding manure alone (M) had a positive increase (66%) in the Haney index over the control (p=0.03) (Fig. 4) after only 1 yr of treatment. Following the 2 yr treatment MTH and MT improved soil health over the three lowest scoring treatments: H, control, and T (p<0.001) (Fig. 4). Additionally, the MTH treatment improved the soil health index over the TH treatment (p=0.03). The MTH and MT treatments improved soil health score by 69% over control (p≤0.03).

Hill bottom

A treatment effect was evident in the hill bottom pasture after 1 yr treatment, with the soil health index of MTH exceeding M values (p=0.04) (Fig. 5). No treatment effect was documented in the 2 yr pasture but plots did follow a similar pattern as other replicates with MT having the highest value and T the lowest (Fig. 5).

Soil organic matter (SOM)

There were no differences in the percentage of SOM for either pasture but patterns began to emerge the 2 yr treatment. At the 2 yr hilltop site, while not statistically significant (p=0.29), the mean SOM in the MTH and MT 23% higher than control (Table 6). In the 2 yr hill bottom site, the SOM content in MT was 39% higher than the control (p=0.1) (Table 6). No trends were detected in either 1 yr treatment groups (p=0.95).

Microbial activity – Solvita CO_2

While no treatment effect (p≤0.05) was detected in microbial respiration for either pasture, trends began to emerge after the 2 yr treatment. The 2-yr hilltop MTH had the highest microbial activity CO_2 release in a 24 h period and differed from H (p=0.08) (Table 6). The MTH CO_2 release was also 48.5% higher than the control.

In the hill bottom site, the 2 yr treatment showed an emerging difference (p=0.06) between the TH and T (Table 6). No similarities or trends were detected in the 1 yr hill bottom group (p=0.47).

PLFA

The PLFA analysis detected a change in arbuscular myccorhizal biomass in the 2 yr hill bottom group only (p=0.04). This biomass change was identified in MT, 454 ± 24 ng/g compared to H treatments, 158 ± 37 ng/g but did not differ from control. No other change in microbial species biomass or community composition was identified.

Soil compaction

Treatments did not impact soil compaction or soil bulk density.

2.4 Discussion

Simulated IMRG grazing mechanisms in this study impacted forage biomass production and soil characteristics across locations and treatment duration. Both positive and negative impacts were present. These were evident in the first year, becoming reliably measurable after two years of treatment in both locations. Overall, MH and MTH treatments benefited forage production, while MT and MTH treatments benefited the soil.

Although trends were evident after one year, it took two years of treatment to measure significant impacts on soil parameters. The MT and MTH treatments produced the greatest improvement on the tested soil parameters while T, H, TH, and C frequently had the lowest values. The combination of manure deposition and trampling (MT and MTH) consistently increased the amount of available nitrogen in the soil. The hilltop pasture, the drier and more degraded of the two sites, showed the largest soil response to treatments where inorganic

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nitrogen exceeded controls by 200% higher than the control and nitrates were over 400% higher than control. In addition to the nitrogen analyses, at the 2 yr hilltop site, there were improvements in the amount of H3A extracted organic phosphorus, calcium (data not shown), and iron (data not shown) in MTH and MT plots.

Although it is not unusual to see a positive effect on soil and plant growth following manure and urine application, the high MT and MTH results suggest that trampling played a key role in soil physical and nutrient cycling properties. Manure alone did not have the highest value in many of the soil parameters and only differed from control in organic N from the 2 yr hilltop site. The ability of trampling to incorporate manure and plant material more quickly into the soil profile in particularly important in an environment with a short growing season. In addition to the positive impact of the MT and MTH treatments, trampling and herbivory alone or in combination, while consistently producing the lowest values, rarely differed from the control plots, suggesting that the less beneficial elements of grazing were still comparable to a pasture at rest (represented by the control). These findings are consistent with several grazing studies in the polar and subpolar regions of the world, and some IMRG studies from the other ecoregions (Jacobo *et al.*, 2006; Teague *et al.*, 2004; Olofsson *et al.*, 2001; McKendrick *et al.*, 1980; McKendrick, 1981).

The soil health, measured by the percentage of SOM, and the Haney soil health index, follow similar trends. These measurements give us a general measure of soil health and the status of the most important soil properties for microbial communities (Haney *et al.,* 2012). Improvements in CO_2 respiration and soil health index in the hilltop pasture could indicate that the microbial activity is increasing along with improving conditions in the soil. The hill bottom site did not follow this trend. SOM matter was highest in manure and trampling combinations while trampling and herbivory improved microbial respiration. This could be due to a higher amount of moisture being retained in the MT treatment which would aid in the SOM decomposition while

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the removal of the plant material and trampling in the TH plots improved the microbial activity by warming the soil and incorporating the existing surface organic residues.

The only difference stemming from PLFA analyses more arbuscular myccorhizal biomass in MT than H in the 2 yr hill bottom pasture. It is difficult to infer anything from this result as it was not replicated in any other year group or pasture, nor was any other microbial group affected. It is possible that the soil temperature, soil moisture, or nutrient input benefitted arbuscular myccorhizal growth and/or that the H treatment favored other groups.

The MT treatment was most positive impact in the hilltop groups while MTH was higher in the hill bottom groups. The difference in the two locations may be explained by soil temperature and moisture. The hill bottom location was consistently colder than the hilltop site by an average of almost 3°C on the soil surface and almost 2°C below the surface (> 3°C in June). It is possible the herbivory treatment allowed the soil to warm earlier and more rapidly in the hill bottom site due to the removal of the insulating plant material. This could have had a positive effect on microbial activity and the related soil properties such as organic matter decomposition and nutrient availability. In the drier hilltop site, the lack of herbivory and application of manure and trampling may have retained more moisture in the soil, precipitating greater positive effects.

In general, grazing treatment had similar effects in both pastures where MH, MTH produced the highest forage yield and MT, and T had a negative impact. The hilltop pasture was more likely to suffer more negative impacts to forage yield from the MT and T treatments, up to a 40% decrease from control. By contrast the hilltop site suffered less deleterious effects from MT and T, up to an 11% decrease compared to controls. In addition to negative impacts, the hilltop site was less likely to see a large increase in yield (8-12% vs controls) when compared to the hill bottom (36-55% increase vs controls). These results could be influenced by the initial condition of the pastures, different dominant plant species, a difference in moisture regime, or

any combination of these factors. Despite the potential for negative impacts in the hilltop site, a cumulative improvement trend was measured with a 29.5% increase (p=0.079) in forage growth averaged over all treatments when 2 yr treatment effects were compared to 1 yr treatment in 2015. This result suggests treatments can provide a net improvement of primary production under simulated IMRG.

In 2016, after the conclusion of the study, forage biomass in the 2 yr plots was harvested in mid-July. The experimental sites had not received any treatment or grazing since the end of the study in Sept. 2015. This post hoc, 3rd year measurement revealed a possible carry-over effect that impacted forage production among treatments (p=0.039). The MT, followed by the MTH treatment, produced the most DW biomass in both locations. We documented a mean increase over control of 10% and 47% in the hilltop and hill bottom pastures, respectively. The lowest forage yield among treatments differed between sites. The H and TH treatments had the lowest values from the hilltop site, a mean 40% decrease from the control. The MH treatment had the lowest values from the hill bottom site, an 11% decrease from the control.

The 2016 forage biomass measurement allowed us to evaluate potential carryover effects from past treatments that impacted new forage production. This measurement yielded some unexpected results. During the experiment, a combination of manure and herbivory produced the greatest amount of DW forage in all groups, in both locations, while a combination of manure and trampling was lower in every case. Yet in the 2016 measurement, the combination of manure and trampling had the largest amount of biomass in each pasture. Contrary to the 2014 and 2015 data, the combination of manure and herbivory had the lowest plant biomass in the hill bottom pasture in 2016. The 2016 measurement also revealed that herbivory alone and in combination with trampling produced approximately 40 % less forage than control in the hilltop pasture. While this measurement was an opportunistic attempt to

capture a snapshot of the carryover effects, it suggests that the increases in N from the MT and MTH treatments were indeed increasing the forage yield in the subsequent year.

The negative T and MT treatment on forage yield results during the experiment may be an artifact of the treatment protocol. Trampling without herbivory often resulted in an abundance of forage but because of the physical trampling, forage stood less than the 8-10 cm height for clipping. We did not lift the plant material to clip even if it was longer than the required height but was trampled to the ground. In addition to the prostrate characteristic of the trampled plots, we visually observed that the grass in the trampled plots often had a similar "new growth" quality as the plots that had been clipped. It is difficult to say which factor influenced the outcomes. The results of the 2016 biomass measurements indicate that the MT treatment had a positive impact on forage production but it is difficult to say whether this is due to the net effect of two-years treatment or an annual benefit that would have been revealed by different sampling protocol.

The amount of bare ground was reduced in all the treatments except for TH and H treatments in the hill bottom site where bare ground increased by 5 to 6%. The result that MT and T treatments reduced bare ground the most is consistent with the claim that animal disturbance (specifically trampling), when applied appropriately, can remediate one of the worst symptoms of degradation. If bare ground is reduced overall, it could potentially reduce soil erosion and the establishment of undesired plant species.

The interpretation of data from this simulated study is consistent with IMRG theory that animal impact can be a net positive on plant and soil characteristics if the timing, intensity and frequency of the disturbance prevent it from initiating a degradation spiral. The lack of differences between the lowest performing treatments and the control plots suggest that in theory, pastures could be grazed and receive the same benefits as taking a pasture out of rotation and potentially improving pasture health. While we have demonstrated that the theories that IMRG methodology is based on, such as the role of trampling, the importance of grazing

based on plant growth, the more heterogeneous deposition of manure, and the prevention of selective grazing, have the potential to be advantageous in sub-arctic Alaskan pastures, however, it is difficult to predict how this would impact a pasture in a live grazing trial.

Although every effort was made to mimic elements of the grazing disturbance, it was not possible to equate the application of grazing treatments to a particular stocking rate. We assumed all the vegetation was eaten, and estimated how much manure and urine would be deposited but it was difficult to determine the trampling pressure, where the time spent standing on each area of ground can be highly variable. While we did not measure a change in soil compaction, we would interpret that as an inconclusive result as it is difficult to separate effects of treatments from the already compacted conditions at the site and the short time frame of the experiment. It is possible that elsewhere, in Alaska, trampling could have a negative impact as soils are sensitive to compaction and erosion (NRCS, 2016).

Missing components of this study are the lack spatial distribution information and an analysis of the changing plant species composition. It is not possible to determine where and what intensity grazing mechanisms would be imposed on a pasture in a simulated study nor how the livestock would select the plant species. Livestock do not graze in a homogeneous manner. How well grazing management can control the spatial distribution of the grazing disturbance mechanisms would ultimately determine the benefit or detriment to the system. In addition to the spatial element, the study lacks the inherent variability and complexity of a live grazing trial. The short duration of the study is a challenge to the interpretation of this data. It is possible that results may reveal negative trends or greater benefits over a longer time period. Despite these shortcomings, we demonstrated that an IMRG system has potential benefits and that many assumptions, such as the beneficial effects of trampling on nutrient cycling, the incorporation of organic residues, the potential of increased biomass production from managed

grazing to be valid in sub-arctic pasture management. These findings should be considered for further study in the form of a live grazing study.

2.5 Conclusion

In the sub-arctic region of Alaska, grazing management is not well studied and the environment is such that it is difficult to apply methodologies developed from vastly different ecosystems. With the looming challenges of climate change, taxed natural resources, and increasing global demand it is imperative that we begin to develop sustainable grazing practices for the environmentally sensitive region of subarctic Alaska. While this study is unable to establish best practices, or validate IMRG grazing strategies in a two-year study time frame, it is an important first step in determining whether the hypotheses on which the methodology is based are effective in the region. We documented a benefit of trampling and manure to nutrient cycling, reduction of bare ground, and if combined with herbivory, a benefit to forage production. Our results were consistent over two different pastures and over a one and two year period. Our results support the results of other research studies that document IMRG benefiting soil health and increasing carrying capacity. This study provides insight into the relative roles of grazing mechanisms and helps to predict the potential impacts of IMRG on plant and soil health in the region. In conclusion, the results from this simulated study suggest that theories that underpin the IMRG method are potentially useful to producers, in the unique Alaskan subarctic environment.

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2.7 Tables

Table 2.1 Temperature and precipitation averages for Fairbanks, AK (Alaska Climate Research Center, 2017)

Month	30-yr monthly mean temp (°C)	2014	2015	30-yr monthly mean precip (cm)	2014	2015
May	9.67	10.73	12.92	1.52	0.15	0.74
June	15.78	14.68	15.42	3.48	9.04	2.62
July	16.94	16.11	16.78	5.49	14.68	7.06
August	13.39	15.04	12.53	4.78	5.82	6.55
September	7.17	7.98	5.78	2.79	7.34	9.5

Table 2.2 Treatment Schedule

Treatment Groups	2014 Treatments	2015 Treatments
Hilltop - 2 yr	Jun-04, Jun-28, Jul-28, Sep-17	Jun-08, Jul-16, Aug-13, Sep-18
Hill bottom - 2 yr	Jun-16, Jul-06, Jul-23, Aug-13, Sep-22	Jun-02, Jun-29, Jul-23, Aug-21, Sep-21
Hilltop – 1 yr	Not established	Jun-09, Jul-17, Aug-14, Sep-19
Hill bottom – 1 yr	Not established	Jun-03, Jun-30, Jul-24, Aug-22, Sep-22

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Table 2.3 Summary split plot analysis of inter-year weather variation and carryover impacts

Hilltop

Impact of inter-year weather variation on treatment	Degrees of freedom	F value	p-value
Treatment	7	24.76	0.000
Replication	2		
Inter-year interaction	7	6.03	0.0002
Impact of carryover + inter-year weather variation on treatment	**Degrees of freedom**	**F value**	**p-value**
Treatment	7	28.75	0.000
Replication	2		
Carryover + Inter-year interaction	7	1.49	0.213

Hill bottom

Impact of inter-year weather variation on treatment	Degrees of freedom	F value	p-value
Treatment	7	24.76	0.000
Replication	2		
Inter-year interaction	7	6.03	0.0002
Impact of carryover + inter-year weather variation on treatment	**Degrees of freedom**	**F value**	**p-value**
Treatment	7	28.75	0.000
Replication	2		
Carryover + Inter-year interaction	7	1.49	0.213

Table 2.4 Summary of treatment effect among treatment groups on dry weight (DW) forage yield of hilltop pasture after one and two years of treatment

Treatments	Mean of 1 yr plots (2014/2015) DW yield (g/m²)	Differs* (p≤0.05)	2 yr plots DW yield (g/m²)	Differs** (p≤0.05)
C (control)	252 ± 34	ab	303 ± 18	ab
H (herbivory)	225 ± 35	ab	292 ± 21	ab
M (manure and urine deposition)	300 ± 25	ab	356 ± 54	a
T (trampling)	103 ± 33	c	63 ± 9	c
MTH	277 ± 31	ab	360 ± 26	a
MT	111 ± 37	c	79 ± 9	c
MH	371 ± 28	a	402 ± 37	a
TH	181 ± 27	bc	143 ± 50	b

Holme-Sidak ad hoc test after log 10 transformation

** *Holme-Sidak ad hoc test*

Table 2.5 Summary of treatment effect among treatment groups on dry weight (DW) forage yield of hill bottom pasture after one and two years of treatment

Treatments	1 yr plots				DW yield (g/m^2) 2 yr plots	Differs (p≤0.05)
	DW yield (g/m^2) 2014	Differs* (p≤0.05)	DW yield (g/m^2) 2015	Differs** (p≤0.05)		
C	700 ± 57	ab	431 ± 20	bc	378 ± 26	b
H	750 ± 51	ab	468 ± 39	ab	510 ± 10	a
M	546 ± 39	ab	348 ± 20	c	505 ± 21	a
T	387 ± 54	ab	67 ± 10	d	90 ± 8	c
MTH	817 ± 43	a	537 ± 19	ab	556 ± 32	a
MT	360 ± 52	b	97 ± 15	d	160 ± 14	c
MH	779 ± 31	ab	589 ± 7	a	548 ± 7	a
TH	684 ± 43	ab	423 ± 29	bc	368 ± 8	b

Kruskal-Wallis ad hoc test

** *Holme-Sidak ad hoc test*

Table 2.6 Possible trends emerging from treatment impact on soil organic matter and respiration after two years of treatment

Treatment	Soil organic matter %		Solvita – 24 hr CO$_2$ respiration (mg CO$_2$/kg soil)	
	Hilltop	Hill bottom	Hilltop	Hill bottom
C	3.6 ± 0.3	6 ± 0.4	105.6 ± 15.6	170.3 ± 7.4
H	3.6 ± 0.4	6.2 ± 0.9	86.0 ± 22.3	167.1 ± 4.6
M	3.6 ± 0.1	6.6 ± 0.4	123.7 ± 21.1	169.4 ± 4.0
T	3.8 ± 0.1	6.0 ± 1.3	109.9 ± 6.1	121.7 ± 23.7
MTH	4.5 ± 0.2	7.4 ± 0.7	156.8 ± 14.8 (p=0.08)*	157.9 ± 8.3
MT	4.5 ± 0.3	8.3 ± 0.6 (p=0.1)*	146.4 ± 15.0	167.1 ± 2.3
MH	4.1 ± 0.7	5.1 ± 0.5	123.3 ± 14.8	153.0 ± 12.4
TH	3.8 ± 0.1	7.4 ± 0.3	102.5 ± 8.3	172.6 ± 5.1 (p=0.06)*

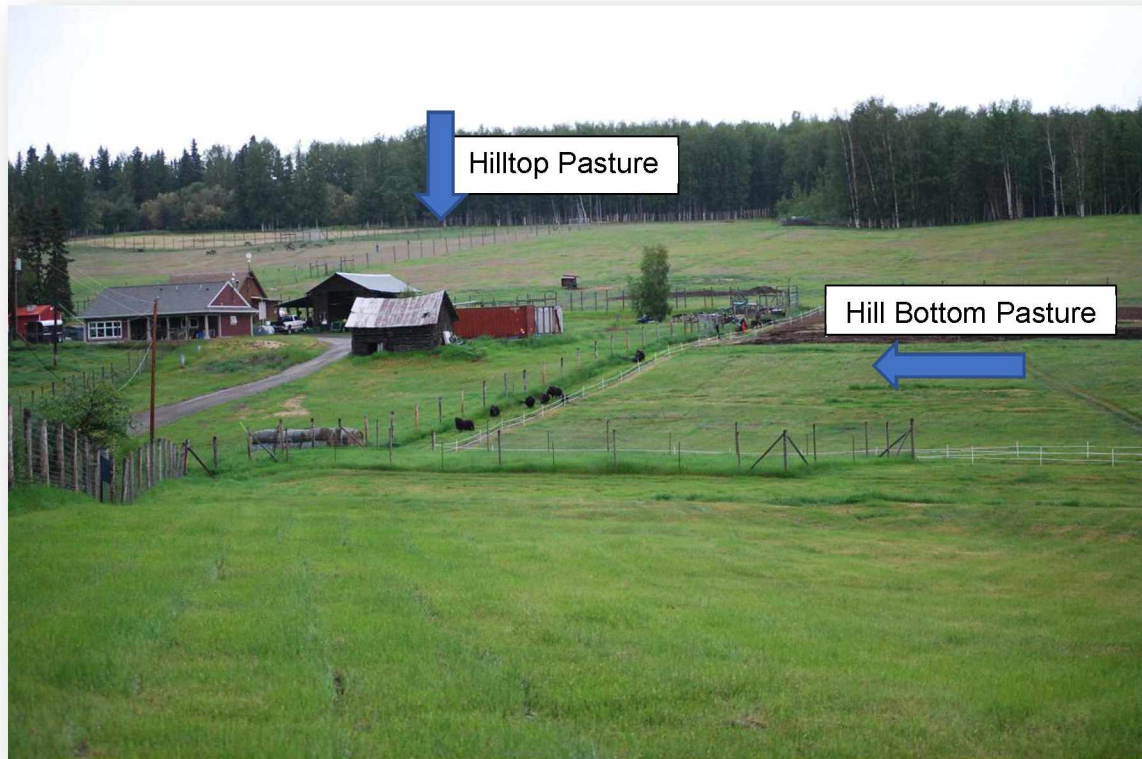* *compared to the lowest treatment measurement*

2.8 Figures

Figure 2.1 Location of simulated study hilltop and hill bottom pastures at the Large Animal
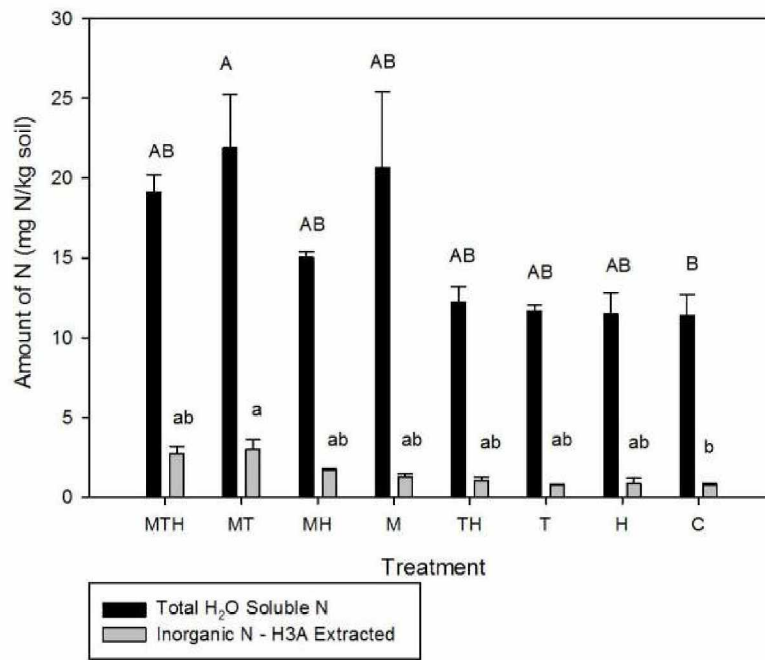Research Station, University of Alaska Fairbanks

Figure 2.2 Total water soluble nitrogen and inorganic nitrogen after two years of treatment at the hilltop pasture (p<0.05)
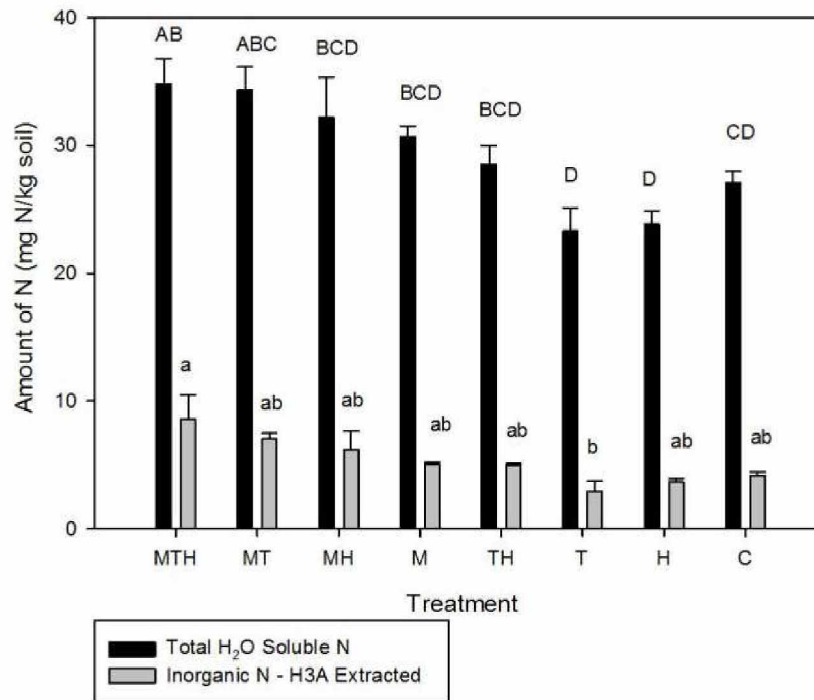
Figure 2.3 Total water soluble nitrogen and inorganic nitrogen after two years of treatment at the hill bottom (p<0.05)
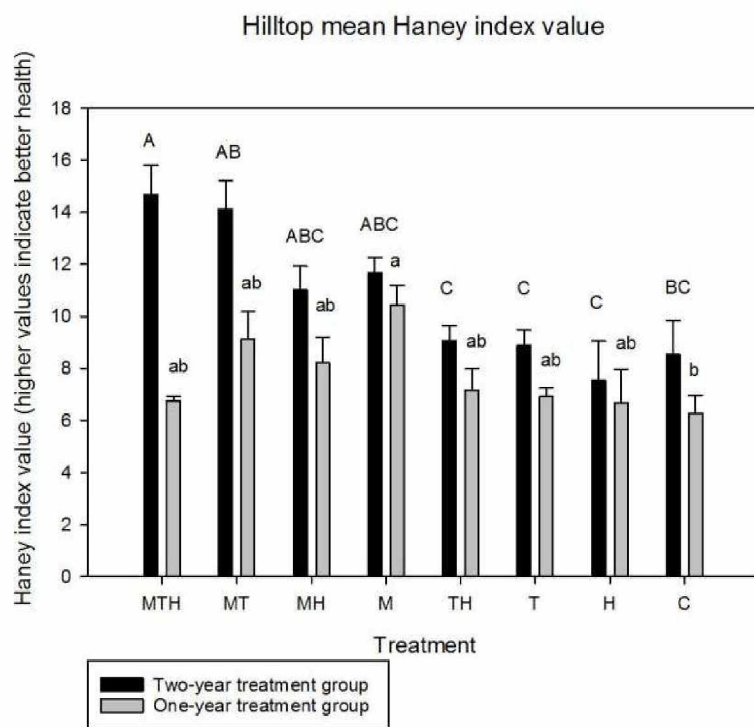
Figure 2.4 One year and two-year treatment measurement of Haney soil health calculation in the hilltop pasture
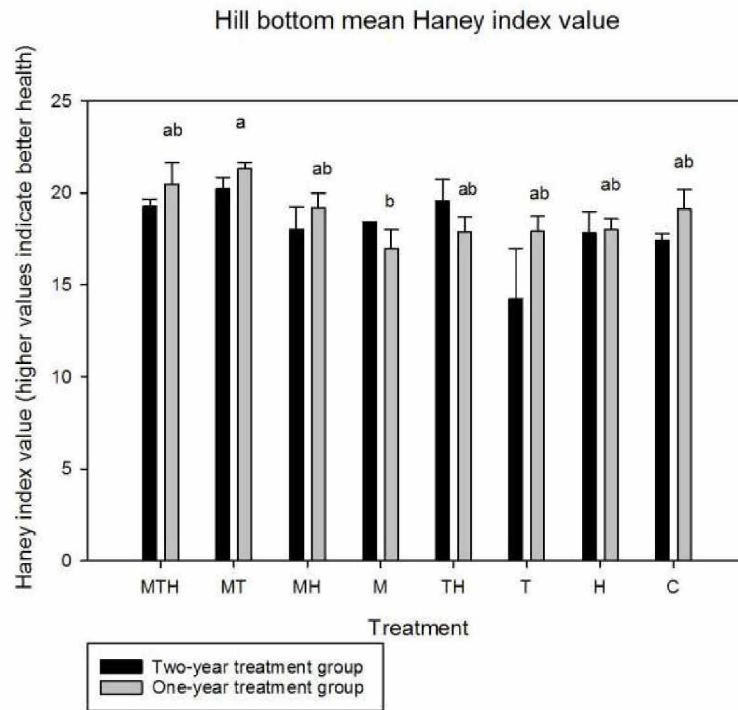
Figure 2.5 One year and two-year treatment measurement of Haney soil health calculation in the hill bottom pasture

Conclusion

These studies were conducted to address some of the fundamental needs of the livestock community in Alaska, focusing on sustainable solutions congruent with the broader, global challenges of climate change, population growth, and limited natural resources. This interdisciplinary research addressed two separate objectives; to evaluate the economic potential of an environmentally sustainable indigenous livestock option (muskoxen) and to aid in the development of sustainable grazing practices for the sub-arctic region by assessing the efficacy of IMRG regimes and the role of simulated grazing mechanisms (herbivory, trampling, and manure/urine deposition).

We met our first objective by constructing an enterprise budget to model costs and returns of a hypothetical farm that raised muskoxen exclusively for their fiber. Within the stated assumptions and marketing conditions, this feasibility study identified a number of scenarios where muskox farming could be profitable. As an indigenous livestock species, it was physically well adapted to the harsh sub-arctic environment while providing good social sustainability due to the uniqueness of the muskoxen and its affiliation to northern culture. We concluded that these attributes in conjunction with the economic potential made the muskoxen a potentially sustainable livestock option in sub-arctic agriculture.

Our second objective was achieved using a simulated grazing study where we applied factorial combinations of the primary grazing mechanisms using the timing and intensity of IMRG methodology. After applying these treatments over the 2014 and 2015 growing seasons, we documented treatment effects on the amount of biomass that was produced and changes in the soil characteristics. The manure and herbivory treatment (MH) had the greatest positive impact on forage biomass production, while manure and trampling (MT) accelerated nutrient cycling. Manure, herbivory, and trampling had a positive impact on both forage and soil.

Trampling improved the soil characteristics by incorporating the organic residues into the soil profile, supporting an important hypothesis of the IMRG methodology.

While neither of these studies established the best sustainable practices for the region, both studies were an important first step in developing methodologies that provide unique solutions and create a broader applied sustainability framework for agriculture in Alaska. Further research is needed to address the important questions advanced by these studies. The economic feasibility study raises questions such as: Who are the consumers? What role would an increase in marketing play? Would improved grazing management make this enterprise more profitable? How would an increase in livestock availability affect the market? How does the price of wild qiviut affect the price of farmed qiviut? Could the enterprise budget framework be applied to other alternative livestock such as reindeer and yak?

The simulated grazing study was limited in time and scope. Would the same results be evident in a live grazing trial? How would the spatial heterogeneity of grazing impact the health of the pasture? Would we document the same results over a longer period of time? What role do the grazing mechanisms have on the plant roots? What result could we expect during a drought year? Does the extra investment in fencing and labor negate potential savings on feed and fertilizer? How does IMRG compare with other grazing strategies in its effects on species composition and overall forage quality? It is my hope that the necessary research to address some of these questions will be conducted in order to move this important body of knowledge forward. Although agriculture is currently not well developed in Alaska, it is possible that these issues will become a matter of critical importance. Alaska has a unique opportunity. While it lacks the investment and existing infrastructure of other, traditional agriculturally productive areas, it has the ability to make sustainability an integral part of any new development or policy. The pressures of climate change and increased demand is sure to change the global ability to

produce food and fiber. With thoughtful, thorough research to guide policies, Alaska will be

poised to meet the challenges for its residents and beyond.