

**Examining best management practices to control the invasion of *Potentilla*
recta within northern intermountain grasslands**

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ABSTRACT

Sulphur cinquefoil (*Potentilla recta* L.) is an invasive plant of concern within grasslands in the intermountain region of the northwestern United States and southwestern Canada. The aim of this research was to identify strategies to control and contain the spread of *P. recta* within northern intermountain grasslands, with a focus on grasslands in southeastern British Columbia, Canada.

In a field study, *P. recta* response to targeted goat grazing conducted once versus twice annually, aminopyralid as a one-time herbicide treatment, and integrated targeted goat grazing and aminopyralid application were examined. Treatment effects on plant community composition were also assessed. Targeted grazing was implemented in 2019 and 2020 and aminopyralid (56 g ai ha⁻¹) was applied once in 2019. Greenhouse studies were conducted to assess *P. recta* growth response in native grass, forb, and grass and forb communities, with and without fertilizer, and to examine the existing prevalence of *P. recta* and other species in the soil seed bank at varying soil depths (0-5 cm, 5-10 cm, 10-15 cm) of *P. recta* invaded grasslands.

Potentilla recta aboveground biomass and number of seed heads declined following targeted grazing, with no differences between grazing once and grazing twice. *Potentilla recta* biomass and seed heads were reduced in the aminopyralid only and targeted grazing plus aminopyralid treatments with no differences between these treatments, indicating both targeted goat grazing and aminopyralid application are possible management options. Increased grass cover was observed in targeted grazing and aminopyralid treatments, suggesting potential off-target effects. Changes in plant community in response to treatments and interactions between treatment, site, and seasonal and annual variations are possible and must be considered as each can influence treatment efficacy.

Potentilla recta growth response did not differ between the native plant communities in the greenhouse; however, *P. recta* above and belowground biomass declined as native plant aboveground biomass increased. In the seed bank, seven of the nine species identified were non-native. The establishment of a productive plant community following *P. recta* control may be an important strategy to mitigate *P. recta* reinvasion or secondary invasion by other invasive species from the seed bank.

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LIST OF ABBREVIATIONS

ae	Acid Equivalent
ai	Active Ingredient
AMF	Arbuscular Mycorrhizal Fungi
ANOVA	Analysis of Variance
AOB	Ammonia-Oxidizing Bacteria
AUM	Animal Unit Month
C	Carbon
Ca ²⁺	Calcium
Cl ⁻	Chlorine
CT	Control
G1	Grazing Once
G2	Grazing Twice
G1H	Grazing Once + Herbicide
G2H	Grazing Twice + Herbicide
H	Herbicide
K ⁺	Potassium
log	Base-10 Logarithm
Mg ²⁺	Magnesium
N	Nitrogen
Na ⁺	Sodium
NH ₄ ⁺	Ammonium
NMDS	Non-Metric Multidimensional Scaling
NO ₂ ⁻	Nitrite
NO ₃ ⁻	Nitrate
PERMANOVA	Permutational Multivariate Analysis of Variance
PLS	Pure Live Seed
PO ₄ ³⁻	Phosphate
SO ₄ ²⁻	Sulphate

1. INTRODUCTION

Grasslands represent approximately 40% of the Earth's land base, providing a large number of ecosystem services, such as biodiversity, water and nutrient cycling, erosion control, climate regulation, forage, and medicines (Murray, Crotty, & van Eekeren, 2012; Zhao, Liu, & Wu, 2020). The establishment and spread of invasive plants have significantly threatened the ecological integrity of grasslands. Invasive plant infestations can alter the structure and function of plant communities, decrease biodiversity, reduce wildlife habitat and forage, alter fire regimes, increase soil erosion, and alter soil moisture and nutrients (DiTomaso, 2000). In western North America, alterations to disturbance regimes by factors such as overgrazing by livestock, land-use changes, changes to fire frequency and intensity, and climate change have facilitated the establishment and spread of invasive plants within grasslands (DiTomaso, 2000; Masters & Sheley, 2001; DiTomaso, Masters, & Peterson, 2010). One such invasive plant is sulphur cinquefoil (*Potentilla recta* L.), which is considered a successful invader within grasslands of western North America (DiTomaso, 2000; Ortega & Pearson, 2005).

Potentilla recta is a perennial forb native to Eurasia that was introduced to North America prior to 1900 (Rice, 1999). Although *P. recta* has spread across North America, it is considered an invader of serious concern in drier climates of western North America, particularly grasslands of the semi-arid intermountain region of the northwestern United States and southwestern Canada (Rice, 1999; Endress, Parks, Naylor, & Radosevich, 2008). *Potentilla recta* invades disturbed sites, such as roadsides, abandoned fields, and clearcuts; however, it also invades natural areas, including grasslands, shrublands, open forests, and seasonal wetlands (Rice, 1999; Naylor, Endress, & Parks, 2005). *Potentilla recta* can live over 10 years and annually produces an average of 6,000 seeds per plant, which can remain viable in the soil for three years (Rice, 1999; Dwire, Parks, McInnis, & Naylor, 2006; Perkins, Parks, Dwire, Endress, & Johnson, 2006). Seeds are only dispersed within 3 m of the parent plant; however, this allows

P. recta to form dense, continuous stands, which threaten native plant communities (Dwire et al., 2006). Research on the management of *P. recta* has primarily occurred in the northwestern United States; however, *P. recta* is a prominent invader within intermountain grasslands to the north in southwestern Canada. To begin addressing this gap, the goal of this research was to identify management strategies that effectively control *P. recta* within northern intermountain grasslands. Research was focused within grasslands in southeastern British Columbia where *P. recta* management was examined through a combination of field and greenhouse studies.

A field study was conducted to identify management strategies to suppress *P. recta* within two intermountain grasslands in southeastern British Columbia by examining the efficacy of using: i) targeted goat herbivory to graze *P. recta* once annually, during the pre-flowering stage, versus twice annually, during pre-flowering and flowering/seedset; ii) aminopyralid as a one-time herbicide treatment; and iii) integrated targeted goat grazing and aminopyralid application versus either targeted goat grazing or aminopyralid application alone. It was hypothesized that combined targeted goat grazing and aminopyralid application would most effectively control *P. recta*, followed by grazing twice, and lastly grazing once, under the assumption that goats would target *P. recta* as a forage plant. We explored changes in plant community composition within treated grasslands to identify unintended (off-target) effects and potential long-term shifts in the plant community. All treatments that included an aminopyralid application were hypothesized to have greater off-target effects and lead to plant communities with more grass cover. Further, to provide insight into seasonal influences on the efficacy and application timing of treatments, the interaction of our treatments with seasonality (spring and summer) was examined and we hypothesized that seasonality would significantly interact with treatment.

To further examine *P. recta* management, two greenhouse studies were conducted to analyze: i) the above and belowground growth response of *P. recta* when grown with and without fertilizer in established native plant communities of varying native plant functional groups, which included grasses, forbs, and grasses and forbs combined; and ii) the existing prevalence of *P. recta* and other species in the soil seed bank at varying soil depths (0 to 5 cm, 5 to 10 cm, 10 to 15 cm) of grasslands invaded by *P. recta* in southeastern British Columbia. We hypothesized *P. recta* suppression would be greatest in the forb only plant community and lowest in the grass only community and fertilizer application would increase the growth response

of both *P. recta* and native plants. We also hypothesized *P. recta* and other non-native species would dominate the soil seed bank but that the number of emerged seedlings from the seed bank would decrease with soil depth.

This thesis is written in manuscript format with five chapters, including the general introduction, followed by a literature review, two research studies, and a final synthesis and conclusions chapter. The literature review in Chapter 2 provides an overview of grassland health and the threat of invasive plants to grasslands. The life history, growth, and mechanisms of invasion of *P. recta* are described and management strategies to control invasive plants are discussed. Chapter 3 focuses on the field study, which examines specific management strategies to control *P. recta* in grasslands within southeastern British Columbia. Chapter 4 further explores the management of *P. recta* through a greenhouse study by assessing its growth response within native plant communities with and without fertilizer. As well, *P. recta* dominance in the soil seed bank is examined. Chapter 5 is the final chapter, which synthesizes all components of this research, presents overall conclusions of the study, including management implications, and provides recommendations for future work. Literature cited is presented in the Reference section that follows Chapter 5.

2. LITERATURE REVIEW

2.1 Grassland Health

Grasslands cover approximately 40% of the Earth's land surface, occurring on all continents, excluding Antarctica (Blair, Nippert, & Briggs, 2014; Zhao et al., 2020). Grasslands are commonly considered ecosystems in which a high cover of grasses and other graminoid vegetation, such as sedges and rushes, occur in an open, typically rolling landscape with little to no tree or shrub cover. The term grassland also applies to ecosystems with significant grass cover among trees, such as open savannas and woodlands, as well as some deserts and shrublands, which contain significant grass cover among succulent plants and/or shrubs (Blair et al., 2014). Grasslands are diverse systems, offering a variety of services, some of which include water and nutrient cycling, carbon sequestration, food production, and climate regulation (Murray et al., 2012). Key functions of a healthy grassland include high net primary production, maintenance of soil stability, capture and beneficial release of water, nutrient and energy cycling, and the support of functional diversity, including plant species (Adams et al., 2016). However, degradation of this critical ecosystem is driving its endangerment worldwide. Primary indicators of grassland degradation include shifts in species composition, loss of biodiversity, reduced biomass production, and soil erosion (Zerga, 2015). Factors contributing to the degradation of grasslands worldwide include land-use changes (Stevens, 2018), overgrazing (Oztas, Koc, & Comakli, 2003; Zerga, 2015), climate change (Polley, Bailey, Nowak, & Stafford-Smith, 2017), woody encroachment by trees and shrubs (Ratajczak, Nippert, & Collins, 2012), and invasive plants (DiTomaso, 2000).

Grasslands are a key land resource within the East Kootenay region of the southern Rocky Mountain Trench in British Columbia, Canada. However, the quality and quantity of these grasslands have been in decline since the 1950s, impacting the long-term health of wild ungulate populations, grassland-dependent species and ecosystems, and the viability of the ranching industry (Phillips & Crowley, 2012). An ecosystem restoration program was implemented in the 1990s to address the decline of grasslands in the region. The program has shown positive results, with 16% of the 25 benchmark sites examined in 2015 showing improved conditions and 60% showing unchanged conditions from a baseline assessment conducted 20 years ago (Forest Practices Board, 2016). Despite the results, threats of ongoing tree

encroachment and ingrowth of forests into restored grasslands, site disturbance from industrial activities and off-road vehicles, poor-grazing practices, and localized over-grazing by elk (*Cervus elaphus* L.) remain. In addition, invasive plants pose a serious threat to grassland restoration, particularly those which were previously considered to be of lower risk, such as sulphur cinquefoil (*Potentilla recta* L.), as their spread is rapidly increasing (Forest Practices Board, 2016).

2.2 Invasive Plants: A Primary Threat to Grassland Health

Invasive plants are a primary management concern within grasslands, a system considered sensitive to invasion (Kulmatiski, 2018). Invasive plants are those that expand beyond their natural range and population density, impacting native species, community dynamics, overall structure and function of ecosystems, and potentially causing significant economic harm (Catford, Jansson, & Nilsson, 2009). For invasion to occur within an ecological community, six phases must be achieved (Catford et al., 2009):

- 1) Transport: Movement of plants or propagules to a new location;
- 2) Introduction: Arrival of plant or plant propagules into a new location;
- 3) Colonization: Survival of introduced plants;
- 4) Naturalization: Survival and reproduction enabling the pioneer population to be self-sustaining;
- 5) Spread: Dispersal of propagules and spread of populations outside of the area where they were first introduced; and
- 6) Impact: Harmful impact of species to ecology and economy.

Characteristics of the invading community and the invasive plant influence the degree of impact of the invasive plant, which can result in long-lasting effects on community structure and function.

Several theories have been proposed to describe invasive plant success, including higher fecundity, greater tolerance to resource constraints, better adaptation to changes in chemical status of the invaded site, the absence of natural enemies within introduced environments, and unoccupied niches (Masters & Sheley, 2001). Disturbance plays a critical role in the creation of empty niches as well as the increase of resources, promoting the rapid establishment and spread of invasive plants within grasslands (DiTomaso, 2000; Catford et al., 2009; Vasquez, James,

Monaco, & Cummings, 2010). As well, disturbance can disrupt species interactions and decrease competition in response to reduced plant diversity (Masters & Sheley, 2001; Zavaleta & Hulvey, 2004; Maron & Marler, 2008a). However, invasive plants are capable of invading undisturbed areas, suggesting invasive plant traits contribute to invasion success, and are not entirely dependent on disturbances. A meta-analysis of 125 invasive plants found that compared with native plants, invasive plants across taxonomic groups exhibit significantly higher performance related traits, such as physiology (i.e., photosynthetic rate, transpiration, leaf construction costs, tissue N content, N use efficiency, water use efficiency), leaf area allocation, shoot allocation, growth rate, size, and fitness (Van Kleunen, Weber, & Fischer, 2010). Invasive plants have also been shown to have greater nutrient use efficiency, giving them a competitive advantage in low-resource environments (Drenovsky, Martin, Falasco, & James, 2008; Funk, 2013). As well, from the perspective of plant:animal interactions, invasive plants are often less palatable than native plants and may be neurotoxic to animals, which favours their survival as foragers may preferentially target native plants (Peters, Johnson, & George, 1996; DiTomaso, 2000). Although invasive plants successfully establish within native plant communities, a recent study by Stotz et al. (2020), using a globally coordinated survey within 22 herbaceous grasslands in 14 countries, found alien plant species do not assimilate into native plant communities, rather they aggregate with other alien species in species-poor, high biomass communities. The aggregation of alien species creates novel communities, where alien-rich patches occur within a mosaic of native-dominated communities. The creation of novel communities can alter site conditions as invasive plants may change soil biotic, chemical, and physical properties, influencing plant-soil feedbacks to sustain their dominance (Eviner, Hoskinson, & Hawkes, 2010; Corbin & D'Antonio, 2012).

Invasive plants can alter soil microbial community composition, which in turn, influences soil chemical dynamics, such as nutrient cycling (Castro-Díez, Godoy, Alonso, Gallardo, & Saldaña, 2014). For example, McLeod et al. (2016) examined changes in soil N and the abundance of ammonia-oxidizing bacteria (AOB) in response to invasions of spotted knapweed (*Centaurea stoebe* L.), downy brome (*Bromus tectorum* L.), leafy spurge (*Euphorbia esula* L.), and *P. recta* within an intermountain grassland in the United States. In comparison to patches of native species, absolute abundance of AOB in *C. stoebe*, *B. tectorum*, and *E. esula* patches was 330%, 620%, and 282% greater. Moreover, soil nitrate (NO_3^-) concentration was 63%, 71%, and 200% greater, respectively, which increased nitrification potential within these invaded patches.

Absolute abundance of AOB in *P. recta* patches was also higher than native patches, at 225%; however, soil NO_3^- concentration did not significantly differ. The study by McLeod et al. (2016) demonstrates that several invasive plant species may alter nutrient dynamics through changes in the soil microbial community; however, the magnitude and impact of alterations differs between species.

Litter decomposition is another means by which soil microbial and nutrient dynamics are altered as the establishment of invasive plants can increase or decrease decomposition rates. Generally, the N concentration in invasive plants is higher and the C:N and lignin:N ratios are lower compared to native plants, accelerating decomposition rates and altering nutrient availability within the invaded ecosystem (Ehrenfeld, 2003; Liao et al., 2008), which favours gram-negative bacteria (Zechmeister-Boltenstern et al., 2015). For example, within grasslands in the Foothills Fescue and Central Parkland natural subregions in Alberta, Canada, the non-native grass, Kentucky bluegrass (*Poa pratensis* L.), has a lower C:N ratio and lignin:N ratio compared to native grasses, including junegrass (*Koeleria macrantha* (Ledeb.) Schult.), rough fescue (*Festuca campestris* Rydb.), needle-and-thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), and plains rough fescue (*Festuca hallii* (Vasey) Piper) (Chuan, Carlyle, Bork, Chang, & Hewins, 2018). The lower C:N and lignin:N ratios led to increased decomposition rates, which can accelerate nutrient and C cycling, altering a fundamental ecosystem process within these grassland systems (Chuan et al., 2018; Chuan, Carlyle, Bork, Chang, & Hewins, 2020). Alternatively, some invasive plants have higher C:N and lignin:N ratios and lower N concentration resulting in significantly lower decomposition rates (Drenovsky & Batten, 2007), decreasing nutrient availability and favouring gram-positive bacteria and fungi (Zechmeister-Boltenstern et al., 2015). For example, the non-native grass, barb goatgrass (*Aegilops triuncialis* L.), which has invaded serpentine grasslands in the state of California within the United States, has higher C:N and lignin:N ratios and lower total N, P, and K compared to native plants (Drenovsky & Batten, 2007). This has led to reduced decomposition rates and consequently, declines in soil nutrient concentrations, exacerbating low nutrient conditions within these grasslands (Drenovsky & Batten, 2007).

Invasive plants may also exude secondary metabolites that have antiherbivore, antifungal, antimicrobial, and/or allelopathic effects (Callaway & Ridenour, 2004; Cappuccino & Arnason, 2006). For example, tall hedge mustard (*Sisymbrium loeselii* L.), a forb invading grasslands

across North America, produces chemicals that inhibit the germination and growth of plants (Bainard, Brown, & Upadhyaya, 2009). As well, arbuscular mycorrhizal fungi (AMF) spore germination is reduced, decreasing the inoculum potential of the soil and adversely affecting the competitive advantage of native plants benefitting from AMF colonization.

In addition to altering soil biotic and chemical properties, invasive plants are known to alter soil physical properties, such as soil porosity (Corbin & D'Antonio, 2012). Norton, Monaco, Norton, Johnson, and Jones (2004) found soil porosity within the A horizon was significantly higher beneath long-term *B. tectorum* invaded areas in comparison to soils beneath shrub canopies and perennial grass-covered interspaces within Wyoming big sagebrush plant communities in northern Utah and southeastern Idaho. The increased soil porosity was attributable to the dense, very fine, and shallow root mass within the A horizon beneath *B. tectorum*, which had 83% more fine roots (< 1 mm diameter) than the A horizon beneath shrub-steppe vegetation. Alterations to soil conditions often degrade plant community composition and ecosystem function, promoting invasive plant persistence and growth (Eviner et al., 2010; Corbin & D'Antonio, 2012).

2.3 Sulphur Cinquefoil (*Potentilla recta*)

2.3.1 Life history and growth

Potentilla recta is a perennial forb native to Eurasia that was introduced to North America prior to 1900 and became well established by the 1950s (Rice, 1999). *Potentilla recta* is considered a minor agricultural weed in eastern North America; however, in drier climates of western North America, including grasslands of the semi-arid intermountain region of the northwestern United States and southwestern Canada, *P. recta* is considered an invader of serious concern (Rice, 1999; Endress et al., 2008). *Potentilla recta* is an early colonizer of disturbed sites, including roadsides, abandoned fields, and clearcuts, but also invades natural sites, including grasslands, shrublands, open forests, and seasonal wetlands (Rice, 1999; Naylor et al., 2005).

Potentilla recta lives up to 10 years, but Perkins et al. (2006) found the age distribution within a population studied in Northeast Oregon to be unevenly skewed towards younger plants, with only 14% of the population over six years of age and approximately half the population two to three years of age. *Potentilla recta* grows one to several stems 15-70 cm in height from a

woody taproot with several shallow, spreading branch roots (Powell, 1996; Rice, 1999). It has pale yellow flowers with five heart-shaped petals and hairy leaves divided into five to seven separate, toothed leaflets. A basal rosette forms in late April to May and the plant bolts and produces flowers from June to late July, setting and dispersing seed from late July to August (Powell, 1996; Rice, 1999). Plants senesce in August; however, fall regrowth is possible following rains in September and October. *Potentilla recta* primarily reproduces by seed. It can annually produce an average of 6,000 seeds per plant, although production of over 15,000 seeds has been recorded (Dwire et al., 2006). Once reproductive, *P. recta* consistently reproduces throughout its lifetime (Dwire et al., 2006; Perkins et al., 2006). Seeds are dispersed within a short distance (<3m) of the parent plant and can remain viable in the soil for three years (Rice, 1999; Dwire et al., 2006). *Potentilla recta* has been shown to reproduce vegetatively; however, results are inconclusive between studies as some indicate *P. recta* solely reproduces by seed and others mention the ability to produce new shoots from the decayed core root mass of the older plant (Powell, 1996; Lesica & Martin, 2003; Dwire et al., 2006).

2.3.2 Mechanisms of invasion

Potentilla recta is an invasive plant of particular concern within the Pacific Northwest (Rice, 1999). Misidentification is considered a factor that has contributed to its spread as it resembles native *Potentilla* species, such as graceful cinquefoil (*Potentilla gracilis* Douglas ex Hook.) (Rice, 1999). *Potentilla recta* invades undisturbed areas; however, disturbance is a key factor driving its dominance. Endress, Naylor, Parks, and Radosevich (2007) found sites with a higher percentage of bare ground were associated with a higher density of *P. recta*. As well, *P. recta* dominance was strongly related to habitat type, with the highest dominance occurring in old fields and lowest in forest, shrub, and grassland habitats (Endress et al., 2007). Although habitat types where *P. recta* most commonly invades have been identified, additional research is needed to understand the mechanisms driving *P. recta* spread and dominance within these landscapes.

Potentilla recta seeds are relatively heavy and do not have distinct structures for wind or animal dispersal (Dwire et al., 2006). Most seeds fall near the parent plant, which enables *P. recta* to expand outward from source plants, facilitating local expansion and the establishment of dense continuous stands. New populations of *P. recta* have established a significant distance

from local populations, indicating long-distance dispersal is possible (Dwire et al., 2006). Humans may act as vectors, as well as seed-eating birds. Animals, most notably wild and domestic ungulates, may also transport seeds in fur and hooves and through endozoochory as they have been shown to graze *P. recta* (Parks, Endress, Vavra, McInnis, & Naylor, 2008; Frost, Mosley, & Roeder, 2013). Seeds are dormant after maturity; however, dormancy is broken by a combination of soil moisture, exposure to light at the soil surface, and diurnal temperature fluctuations (Baskin & Baskin, 1990). After burial, seeds remain nondormant in the soil for over two years. As such, buried seeds are able to germinate during any month of the growing season if seeds are brought to the soil surface following a disturbance and moisture in non-limiting (Baskin & Baskin, 1990). Baskin and Baskin (1990) found germination to be relatively high, ranging from 41-87% in the fall, following the after-ripening of seeds during the summer. In comparison to its native congener, *P. gracilis*, McIver and Erickson (2012) found *P. recta* invests three times as much energy in seed production. As well, seed germination is nearly twice as many (35.0% versus 19.5%) and seeds consistently germinate for over eight months following wetting, whereas the majority of *P. gracilis* seed germination occurs within two months following wetting. The high input and viability of seeds can allow *P. recta* to dominate the seed bank within infested areas (Dwire et al., 2006). The seed bank has a significantly greater impact on seedling germination than seed rain, suggesting seed bank contribution enables *P. recta* patches to perpetuate (Tuitele-Lewis, 2005). However, environmental factors, such as water and salt stress, have a greater effect on seed germination than seed bank or seed rain (Kiemnec & McInnis, 2009). As well, declines in *P. recta* survival can decrease population size of the species more so than a decline in recruitment (Lesica & Martin, 2003). Further research is needed to examine the role of the seed bank as a mechanism establishing and sustaining *P. recta* populations and the effect of reducing seed source to manage *P. recta* invasion.

In addition to high fecundity, high growth rate and competitive advantage are commonly recognized as mechanisms driving invasive plant success. A study by Tuitele-Lewis (2005) found *P. recta* within an old agricultural field in the Blue Mountains of northeastern Oregon did not exhibit a higher or lower relative growth rate in comparison to native species. However, relative growth rate was calculated from plants growing within high-density *P. recta* patches rather than those growing with native plants, which may underestimate the competitiveness of *P. recta*. An experiment conducted by Callaway, Montesinos, Williams, and Maron (2013) revealed

P. recta growth was higher in soil conditioned by the native fescue, Idaho fescue (*Festuca idahoensis* ElmerElmer), in comparison to soil conditioned by *P. recta*, suggesting monocultures of *P. recta* create a negative plant-soil feedback loop, impacting *P. recta* growth performance. *Potentilla recta* growth may also be impacted by environmental factors such as drought, which reduce plant height (Burkle & Runyon, 2016). Further, results concerning competitive advantage are inconclusive. *Potentilla recta* is known to reduce native plant biomass with little effect from elevated resource supply, suggesting *P. recta* exerts strong competitive dominance over individual native grassland species (Maron & Marler, 2008b). In contrast, Endress et al. (2007) argue *P. recta* dominance is primarily a result of the interaction between *P. recta* invasion, disturbance, and changes to land use/land cover rather than competitive superiority. As such, *P. recta* is suggested to be a “passenger” of fundamental environmental changes that are limiting native vegetation.

2.4 Management of Invasive Plants in Grasslands

Several methods, including mechanical, cultural, biological, and chemical, can be used to manage invasive plants. Approaches commonly used to manage *P. recta* invasion in grasslands include targeted (prescribed) grazing, herbicide application, and native plant seeding. Biological control agents have not been employed to control *P. recta* because of its close genetic relationship to native *Potentilla* species, and the threat it would pose to native species decline (Rice, 1999; DiTomaso et al., 2013). Despite the various options to control *P. recta*, research is limited on which management strategy or combination of strategies most effectively addresses *P. recta* invasion.

2.4.1 Targeted grazing

Targeted (also known as ‘prescribed’) grazing is a cultural invasive plant management approach that involves the application of livestock, such as cattle, sheep, and goats, at a specific season, duration, and intensity to control invasive plants (Frost & Launchbaugh, 2003). Targeted grazing is becoming an increasingly popular strategy to selectively graze invasive plants to change plant community composition towards a native plant dominated system. Targeted grazing places the invasive plant at a competitive disadvantage as grazers target the plant when it is most vulnerable and grazing efforts are concentrated on the target invasive rather than native

vegetation (Frost & Launchbaugh, 2003). However, efficacy is dependent on appropriate selection of a grazer, timing, intensity, and frequency of grazing, as well as understanding the ecology of the invasive plant being targeted (Frost & Launchbaugh, 2003; Rinella & Hileman, 2009).

Selecting the grazer most suitable to control an invasive plant is a critical step for management success. Cattle are commonly used to manage grasses as they are bulk feeders with large rumens able to ferment large quantities of low-quality fibrous material (Frost & Launchbaugh, 2003; Burritt & Frost, 2006). Sheep have a narrow muzzle and a large rumen relative to body mass enabling them to selectively graze and tolerate high fiber contents resulting in a diet dominated by forbs. Goats have narrow, strong mouths which can strip leaves from woody stems, and they also have a large liver mass relative to cattle and sheep enabling them to more efficiently process secondary compounds, such as tannins and terpenes (Frost & Launchbaugh, 2003; Burritt & Frost, 2006). As such, goats are appropriate grazers to manage woody invasive plants and plants containing various allelochemicals.

Targeted grazing requires grazing to be conducted when the plant is palatable to the grazer and most vulnerable to defoliation, which varies between invasive plant species (Frost & Launchbaugh, 2003). For instance, targeted grazing of *E. esula* by sheep is most effective prior to flowering (Rinella & Hileman, 2009; Rinella & Bellows, 2016) whereas targeted grazing of yellow starthistle (*Centaurea solstitialis* L.) by goats is most effective during the late-season (July-November) (Goehring, Launchbaugh, & Wilson, 2010). The grazing intensity required to effectively control invasive plants is also variable. Grazing intensity, identified as low, moderate, and high, is commonly measured by stocking rate, which is the number of animals on a given amount of land over a specific period of time (Sollenberger, Agouridis, Vanzant, Franzluebbers, & Owens, 2012; Sandhage-Hofmann, 2016). Pywell et al. (2010) found low intensity grazing with cattle conducted in spring and autumn reduced Canada thistle (*Cirsium arvense* (L.) Scop.) cover more than high intensity grazing within grasslands in the United Kingdom. In contrast, De Bruijn and Bork (2006) found high intensity-low frequency (pulsed) grazing by cattle most effectively reduced *C. arvense* cover within permanent pastures in central Alberta, Canada. Grazing frequency is a key factor to consider for management success as grazing may need to occur more than once over a growing season (Benzel, Mosley, & Mosley, 2009) and/or over multiple years for best control (Rinella & Bellows, 2016).

Potentilla recta is considered a plant avoided by foragers as it has low palatability, with a tannin content of 17 to 22% dry weight (DiTomaso et al., 2013). However, targeted grazing is considered a viable approach to manage *P. recta*. Parks et al. (2008) recommended the use of cattle to manage *P. recta* populations as cattle grazed *P. recta* in early summer within a rangeland in northeastern Oregon, resulting in smaller plants with fewer flowers and seed heads. Targeted sheep grazing conducted during the early flowering and late flowering-early seedset phenological stage within a rangeland in northwestern Montana reduced viable seed production by over 95% (Mosley, Frost, Roeder, & Kott, 2017). *Potentilla recta* yield in the subsequent summer was also over 40% lower. As well, sheep had the benefit of preferentially targeting *P. recta* over native forbs (Masin, Nelson, & Valliant, 2018). Targeted grazing conducted by goats is another option to manage *P. recta* as goats are able to efficiently process the high tannin content of *P. recta* and reduce seed viability once seed passes through the digestive tract (Frost & Launchbaugh, 2003; Frost et al., 2013). Currently, the use of goats as targeted grazers to combat *P. recta* invasion within grasslands is being explored in the East Kootenay region of British Columbia (Carignan, 2017; Murphy, 2017).

Optimal timing and intensity of targeted grazing to reduce aboveground productivity and seed production of *P. recta* was examined by Frost and Mosley (2012) over two years within a foothill rangeland in southwestern Montana. This experiment involved clipping *P. recta* plants during preflowering, flowering, and/or seedset to two stubble heights (7.5 cm or 15 cm) for a total of seven different timing treatments. All clipping treatments reduced aboveground biomass, excluding plants clipped at 15 cm during pre-flowering within year two, which was a wetter year. All clipping treatments at each time or combination of timings reduced the number of *P. recta* buds, flowers, fruits, and seeds in both treatment years. As well, plants clipped once to 7.5 cm or 15 cm during flowering or seedset reduced seed production by 99 to 100%. Frost and Mosley (2012) concluded that targeted grazing can be applied once per season during flowering or seedset to reduce biomass and viable seed production of *P. recta*. Performing targeted grazing during seedset poses the question of whether livestock will pass viable seed through their digestive tract, contributing to weed expansion. Frost et al. (2013) examined the recovery and viability of immature and mature *P. recta* seeds from the feces of sheep and goats. Prior to oral gavage, seed viability averaged 36% for immature seeds and 76% for mature seeds, while viability of recovered seeds averaged 3% for immature seeds and 27% for mature seeds. Nearly

all (98%) of the viable seeds recovered were excreted by sheep and goats within two days of consumption. Viable seeds were not recovered from sheep or goats after three days following consumption. Viability estimations are likely high as seeds were administered by oral gavage and therefore avoided damage from mastication. Frost et al. (2013) recommends keeping sheep and goats in a corral for three days following consumption of *P. recta* plants during flowering or later plant growth stages to ensure viable seeds are excreted before livestock are moved to a new area.

2.4.2 Herbicide application

Herbicide application is a common approach used to manage invasive plants within grasslands (DiTomaso et al., 2010). Herbicide effectiveness is dependent on the ability of the active ingredient to reach its target site, such as an enzyme or protein, creating a biological response that harms the plant. Adjuvants, such as surfactants, spreader-stickers, and penetrants, are commonly added to the herbicide formulation to improve herbicide performance or application characteristics (Curran, McGlamery, Liebl, & Lingenfelter, 1999). Herbicides applied in grasslands typically have low toxicity to vertebrates and invertebrates; however, herbicides pose other risks, including the potential for ground or surface water contamination, wind-blown herbicide movement on soil particles, and damage to desirable plants (Masters & Sheley, 2001; DiTomaso et al., 2013). Herbicides, such as glyphosate, may be nonselective, impacting many types of plants (trees, grasses, forbs, etc.), whereas others, such as picloram, are selective herbicides, only impacting a specific type of plant, such as broadleaf plants (Rinella, Maxwell, Fay, Weaver, & Sheley, 2009). In some cases, herbicide application can exacerbate the invasive plant problem because of its damage to native plants, which would increase niche space and resources for the invasive plant during recruitment from the seed bank. For example, Rinella et al. (2009) applied the broadleaf selective herbicide, picloram, within a grassland in Montana to manage exotic forbs, including *E. esula*. However, abundance of *E. esula* increased in response to decreased native-forb cover due to herbicide application. As well, all exotic species eventually recovered after spraying, whereas herbicide application caused long-term suppression of several native forbs. In contrast, herbicide application can have little to no negative impacts on native species communities. Harrington, Peter, and Devine (2014) applied the broadleaf selective herbicide, aminopyralid, on an invaded meadow within the Washington Cascades over two years and found little to no negative impacts on abundance and richness of native species when applied

at 30 g ae ha⁻¹. Identification of the appropriate compound, timing, and application rates are necessary to reduce herbicide impacts to native plants, while still achieving invasive plant control. As well, understanding the interaction between native plants, herbicide persistence, and reapplication intervals is needed to minimize off-target effects to native plant communities (Crone, Marler, & Pearson, 2009).

Various herbicides have been used to control *P. recta*, including 2,4-D, aminocyclopyrachlor + chlorsulfuron, aminocyclopyrachlor + metsulfuron, aminopyralid, picloram, triclopyr, glyphosate, chlorsulfuron, metsulfuron, and hexazinone (DiTomaso et al., 2013). Endress et al. (2008) examined the efficacy of the herbicides dicamba + 2,4-D, metsulfuron-methyl, triclopyr, glyphosate, and picloram at two rates of application (low and high) and three application times (early summer, fall, and combined early summer/fall) to control *P. recta* within a grassland in northeastern Oregon. Each herbicide reduced *P. recta* abundance; however, picloram, applied at a rate of 0.28 kg ae ha⁻¹ and 0.56 kg ae ha⁻¹, was the most effective, with no difference in control between the application rates (Endress et al., 2008). As well, its effects continued six years following application (Endress, Parks, Naylor, Radosevich, & Porter, 2012). However, within *P. recta* infested grasslands, picloram reduces native forb cover (Sheley & Denny, 2006). Integrating herbicide application with native seeding will likely encourage a healthier plant community that is more resistant to *P. recta* reinvasion as well as invasion from other invasive plants, relative to plots strictly using herbicide (Sheley & Denny, 2006; Endress et al., 2008).

2.4.3 Seed bank analysis and revegetation

Seed bank analysis and revegetation are undervalued strategies within invasive plant management (Kettenring & Adams, 2011; Gioria, Pyšek, & Moravcová, 2012; Vandvik, Klanderud, Meineri, Måren, & Töpper, 2016). Seed bank analysis of an invaded grassland identifies the dominance and persistence of the invasive plant within the seed bank, as well as the prevalence of native species and other undesirable species (Gioria et al., 2012; Vandvik et al., 2016). Following invasive plant control, niches are opened, providing an opportunity for desirable species to establish from the seed bank. However, in communities that have been invaded for an extended period, desirable species may be rare or absent from the seed bank, which presents the risk of invasive plants reestablishing in the opened niche or other undesirable

species establishing and becoming dominant (Mangold, 2012a). For example, the release of the Eurasian root weevil, *Cyphocleonus achates* (Fahraeus), within two fields in western Montana, reduced *C. stoebe* populations; however, another weed, *B. tectorum*, subsequently expanded following *C. stoebe* decline (Story, Callan, Corn, & White, 2006). A seed bank analysis is important to determine whether active revegetation is needed to suppress the invasive plant or other undesirable species.

Revegetation is considered the best long-term alternative for managing invasive plants on sites that lack desirable species (Masters & Sheley, 2001). However, a recent review and meta-analysis of research papers on invasive plant control revealed only one-third of studies considered revegetation (Kettenring & Adams, 2011). As well, the practice of revegetation is challenging and is often met with failure as desirable species do not consistently establish and invasive plants often reinvade due to their sizeable seed bank (Carpinelli, Sheley, & Maxwell, 2004; Mangold, 2012a). An integrated approach involving the control of the invasive plant through methods such as herbicide application, in combination with native plant seeding, presents a greater opportunity for invasive plant management success (e.g., Masters & Nissen, 1998; Sheley, James, & Daniel, 2001; Endress et al., 2012).

2.4.4 Integrated management

A single method to manage invasive plants within grasslands is often less effective for long-term control than a combination of management techniques that form an integrated management approach (DiTomaso, 2000; Masters & Sheley, 2001; DiTomaso et al., 2010). An integrated management plan must consider the biology and ecology of the invasive plant and invaded community, as well as the causes of plant invasion, to identify the most appropriate techniques to manage the invasive plant (Masters & Sheley, 2001). The integrated management plan also needs to align with overall grassland management objectives and plans to be successful.

Research has examined the integration of herbicide and native plant seeding to manage *P. recta* invasion within grasslands. Endress et al. (2012) found a one-time application of the herbicide picloram effectively controlled *P. recta* for over six years within a grassland in northeastern Oregon. However, overall exotic plant cover was not reduced as annual exotic grasses replaced *P. recta*. Alternatively, Endress et al. (2012) seeded native perennial grasses in

combination with herbicide application and found this integrated approach most effectively controlled *P. recta* while increasing native species abundance.

Research has also examined the use of herbicides (Endress et al., 2008; Endress et al., 2012) and targeted grazing (Frost & Mosley, 2012; Mosley et al., 2017) to control *P. recta* within grasslands, although the integration of these techniques as a control strategy has not been assessed. However, research on the management of other invasive plants using this integrative approach has been conducted. Lym, Sedivec, and Kirby (1997) conducted a four-year experiment within a grassland in North Dakota to examine herbicide treatments with targeted goat grazing compared to herbicide application and targeted goat grazing alone to control *E. esula*. Targeted grazing with an annual fall application of picloram + 2,4-D quickly reduced *E. esula* density and sustained control longer in comparison to other treatments. Further, Sheley, James, and Martin (2004) found the reduction of *C. stoebe* cover and biomass within abandoned hayfields in western Montana following the application of 2,4-D in the spring combined with repeated targeted sheep grazing was greater than targeted sheep grazing and 2,4-D application alone. The success of these integrative approaches suggests the combination of herbicide and targeted grazing may be a viable option to control *P. recta*.

Potentilla recta invasion is of growing concern in grasslands within southwestern Canada, including grasslands in the southern Rocky Mountain Trench of southeastern British Columbia. Examining the integration of herbicide and targeted grazing in comparison to herbicide application and targeted grazing alone will help identify a management treatment to effectively suppress *P. recta* within this region of British Columbia. In addition, identifying native plant communities that suppress *P. recta* and assessing the seed bank to determine revegetation needs will help develop a best management approach to control *P. recta* by coupling invasive plant management treatments with the restoration of the native grassland community. The combination of these efforts will aid in the recovery of healthy grassland communities resilient to *P. recta* reinvasion.

3. SUPPRESSION OF *POTENTILLA RECTA* BY TARGETED GOAT GRAZING AND AMINOPYRALID ON NORTHERN INTERMOUNTAIN GRASSLANDS¹

3.1 Preface

Research on *P. recta* management via targeted grazing and herbicide application has occurred in grasslands in the northwestern United States. However, *P. recta* is prevalent in grasslands in southwestern Canada and research is needed to identify management strategies that effectively control *P. recta* within northern intermountain grasslands. In this chapter, the efficacy of targeted goat grazing (once vs twice), the application of the herbicide, aminopyralid, and a combined treatment, are examined as management strategies to control *P. recta* in northern intermountain grasslands. Treatment effects on plant community composition and the interaction between treatments and seasonality (spring and summer) are also explored.

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3.2 Abstract

Sulphur cinquefoil (*Potentilla recta* L.) is an invasive perennial forb threatening grasslands in western North America. To identify best management strategies to control *P. recta*, we examined targeted goat grazing conducted once (pre-flowering) annually versus twice (pre-flowering and flowering/seedset) annually, aminopyralid as a one-time herbicide treatment, and integrated targeted goat grazing and aminopyralid application as management strategies. We also examined treatment effects on plant community composition and the interaction between treatments and seasonality (spring and summer). Two intermountain grasslands in British Columbia, Canada, were treated, one with targeted grazing treatments only and one with targeted grazing and herbicide treatments. Targeted grazing treatments were implemented in 2019 and 2020 and aminopyralid was applied once in 2019 at a rate of 56 ai g ha⁻¹. *Potentilla recta* aboveground biomass and number of seed heads declined following targeted grazing treatments at both field sites in 2019 and 2020 when compared to the control, with no differences between grazing treatments. In May 2020, prior to the implementation of targeted grazing for the second year, a decrease in *P. recta* biomass was not measured in the targeted grazing treatments, but biomass was 87-99% less in the herbicide only and targeted grazing plus herbicide treatments. In July 2020, declines in biomass and seed heads in all herbicide treatments did not differ from grazing twice, and aminopyralid effects did not differ based on whether targeted grazing was added, suggesting an integrated approach may not be necessary. Increased grass cover was observed at each site in both the targeted grazing and herbicide treatments suggesting potential off-target effects, which must be considered when management objectives aim to promote healthy native grassland plant communities. Changes in plant community in response to treatments and interactions between treatment, site, and seasonal and annual variations are possible and must be considered as each can influence treatment efficacy.

3.3 Introduction

Grasslands are a key land resource within western North America, providing multiple ecosystem services such as biodiversity, wildlife habitat, and water and nutrient cycling, as well as cultural value through the provision of livestock forage, food, medicinal plants, and fiber (Zhao et al., 2020). However, grassland degradation has been prevalent throughout western North America, with invasive plants posing a primary threat to the integrity of grasslands, a

system considered sensitive to invasion (Kulmatiski, 2018). Sulphur cinquefoil (*Potentilla recta* L.) is one of many invasive plants identified as a major weed damaging grassland integrity within western North America (DiTomaso, 2000).

Potentilla recta is a perennial forb native to Eurasia that was introduced to North America prior to 1900 and became well established by the 1950s (Rice, 1999). *Potentilla recta* is a minor agricultural weed in eastern North America; however, in drier climates of western North America, including grasslands of the semi-arid intermountain region of the northwestern United States and southwestern Canada, *P. recta* is an invader of serious concern (Rice, 1999; Endress et al., 2008). *Potentilla recta* is an early colonizer of disturbed sites, including roadsides, abandoned fields, and clearcuts, but also invades natural sites, including grasslands, shrublands, open forests, and seasonal wetlands (Rice, 1999; Naylor et al., 2005). It is a long-lived forb, living over 10 years, and it produces an average of 6,000 seeds per plant, which can remain viable in the soil for three years (Rice, 1999; Dwire et al., 2006; Perkins et al., 2006). The longevity of *P. recta*, its seed production, and seed viability contribute to its ability to maintain its population at the invaded site (Rice, 1999; Dwire et al., 2006). Management of *P. recta* requires depleting the seed bank and targeting mature plants to reduce their survivability and reproduction (Perkins et al., 2006; Lesica & Ellis, 2010).

Research on the management of *P. recta* has primarily occurred within the northwestern United States, although the spread and establishment of *P. recta* is becoming of increasing concern within southwestern Canada. To our knowledge, this study is the first to examine *P. recta* management within grasslands of the intermountain region of Canada, representing the most northerly study of this invasive species within North America. Control of *P. recta* has been examined through simulated grazing via clipping (Frost & Mosley, 2012), targeted grazing with sheep (Mosley et al. 2017), and herbicides (Sheley & Denny, 2006; Endress et al., 2008). Sheep have been used to suppress *P. recta*, reducing yield and seed viability (Mosley et al., 2017); however, goats and cattle are other potential livestock candidates as both are known to graze *P. recta* (Parks et al., 2008; Frost & Mosley, 2012). The herbicides 2,4-D, dicamba + 2,4-D, 2,4-D + clopyralid, 2,4-D amine, metsulfuron-methyl, triclopyr, glyphosate, and picloram have been applied to control *P. recta* (Sheley & Denny, 2006; Endress et al., 2008), with picloram identified as the most effective herbicide, achieving control six years post-treatment (Endress et al., 2012). Although picloram effectively suppresses *P. recta*, harm to native forbs is a

significant risk (Sheley & Denny, 2006). Aminopyralid is a broadleaf herbicide that may be an alternative to picloram as it has reduced risk to desirable native species, yet is effective on many hard to control invasive plants (Halstvedt, 2012; Harrington et al., 2014).

Targeted grazing and herbicide are recommended as effective strategies to manage *P. recta*; however, treatment efficacy between the two treatments has not been directly compared. As well, both strategies pose the risk of adversely affecting non-target vegetation. The utilization of livestock presents the risk of consumption of non-target species (e.g., Kirby, Hason, & Sieg, 1997; Masin et al., 2018; Mosely et al., 2017). For example, goats consume a wide array of vegetation, including forbs, woody plants, and grass, and their selectivity of non-target plants is influenced by various factors, including the availability and abundance of vegetation on site, nutritional needs, experiences, and inherited and learned behaviors (Larson, Barry, & Bush, 2015). Further, the application of a broadleaf herbicide poses the risk of reducing native forb cover and richness, which has potential long-term effects on plant community composition if non-target plants are unable to recover following herbicide application (Rinella et al., 2009). Plant community assessments are an important component of invasive plant management efforts to identify potential off-target effects and work towards mitigating these effects.

Assessment of annual and seasonal variations in the target plant response and plant community composition are also important components of invasive plant management efforts as these variations may influence treatment efficacy and the optimal timing of treatment implementation. For example, precipitation is a factor contributing to the variation in *P. recta* response, influencing the effectiveness of management treatments, as shown by Frost and Mosley (2012) who observed greater aboveground biomass and seed production of *P. recta* during a wetter year, leading to reduced efficacy of clipping treatments. Further, seasonal shifts in plant community in response to summer-induced dormancy and senescence is common within grasslands in the intermountain region (Rice, Toney, Bedunah, & Carlson, 1997; Wikeem & Wikeem, 2004). Examining treatment by season interactions and seasonal shifts in plant community responses will help identify a time period in which the target species is most vulnerable to treatments and non-target species are least vulnerable based on life-cycle stage (DiTomaso & Smith, 2012).

The purpose of this research was to identify best management strategies to suppress *P. recta* within two intermountain grasslands in southeastern British Columbia, Canada.

Specifically, we examined the efficacy of using: i) targeted goat herbivory to graze *P. recta* once annually, during the pre-flowering stage, versus twice annually, during pre-flowering and flowering/seedset; ii) aminopyralid as a one-time herbicide treatment; and iii) integrated targeted goat grazing and aminopyralid application versus targeted goat grazing and aminopyralid application alone. The combined targeted goat grazing and aminopyralid application was hypothesized to be the most effective treatment in suppressing *P. recta*, followed by grazing twice, and lastly grazing once, under the assumption that goats would target *P. recta* as a forage plant. We explored changes in plant community composition in the treated grasslands to identify off-target effects and potential long-term shifts in the vegetative community. All treatments that included an aminopyralid application were hypothesized to have greater off-target effects and lead to plant communities with more grass cover. Finally, to provide insight into seasonal influences on treatment efficacy and timing, the interaction of our treatments with seasonality (spring and summer) was examined and we hypothesized that seasonality would significantly interact with treatment.

3.4 Materials and Methods

3.4.1 Study sites

A two-year study was conducted from 2019 to 2020 on two degraded grasslands within the East Kootenay Region of British Columbia, Canada, in the southern Rocky Mountain Trench. One site was located in Wycliffe ($49^{\circ}40'5.41''N$, $115^{\circ}52'55.01''W$) and the other in the northern reach of Tobacco Plains Indian Band (Yaqit ?a·knuqli ‘it) reserve ($49^{\circ} 4'18.65''N$, $115^{\circ} 7'9.66''W$) (Fig. 3.1). The plant community at both sites consisted of a mix of native and non-native grasses and forbs, with limited shrub cover and a biological soil crust layer (Table 3.1).

Very dry conditions with moisture deficits during the growing season are climatic characteristics of low elevation grasslands in the East Kootenay Region (MacKillop, Ehman, Iverson, & McKenzie, 2018). Average summer season (April-September) temperatures from 2010-2020 were $14 \pm 5.7^{\circ}C$ and $16 \pm 5.7^{\circ}C$ at Wycliffe (Cranbrook Airport, BC, $49^{\circ}36'36.00''N$, $115^{\circ}46'48.00''W$) and Tobacco Plains (Eureka Ranger Station, MT, $48^{\circ}53'52.08''N$, $115^{\circ} 3'51.84''W$), respectively, and average winter season (October-March) temperatures were $-1.8 \pm 7.0^{\circ}C$ and $1.2 \pm 6.8^{\circ}C$, respectively. Average total summer precipitation from 2010-2020 was 188 ± 70 mm and 207 ± 68 mm at Wycliffe and Tobacco

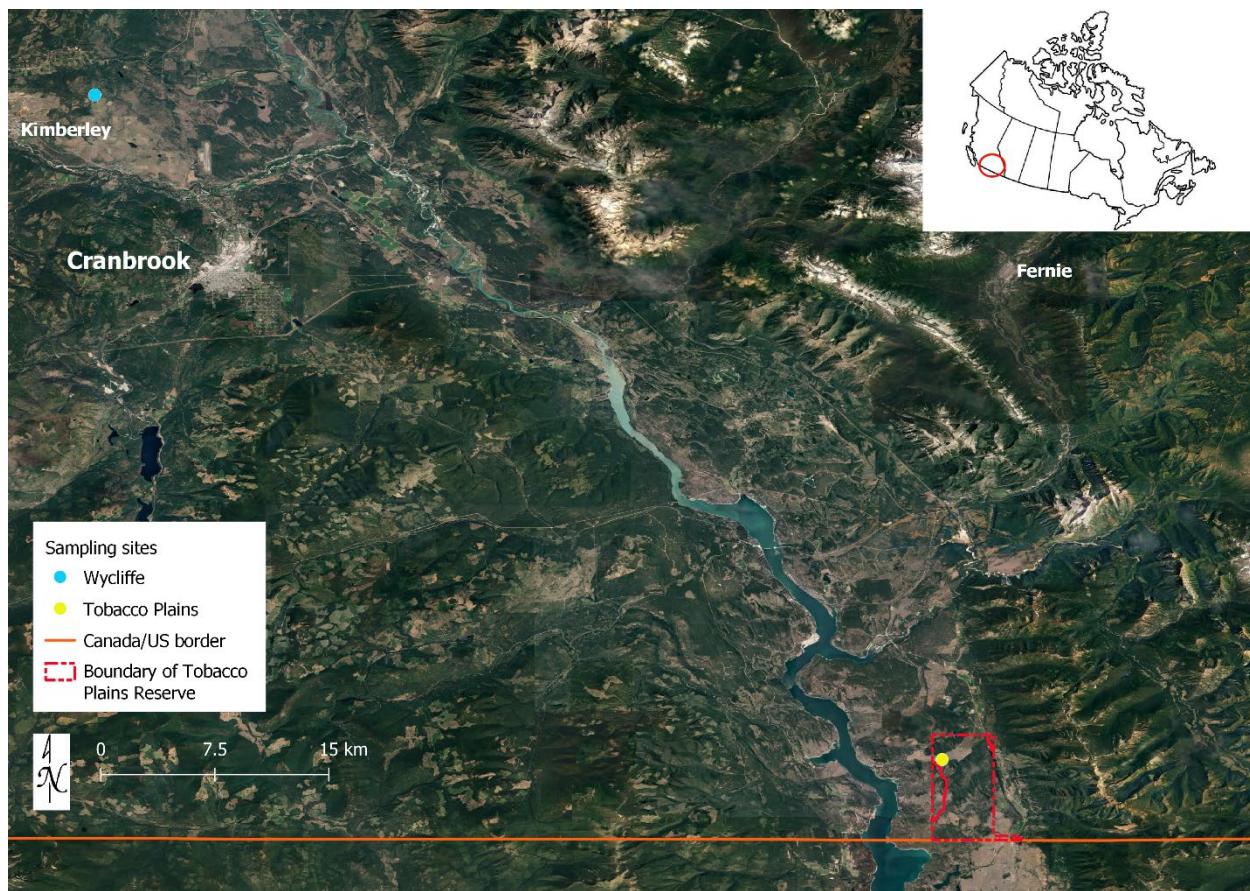


Figure 3.1. Location of the Wycliffe and Tobacco Plains study sites within southeastern British Columbia, Canada.

Plains, respectively, and average total precipitation during the winter season was 178 ± 56 mm and 183 ± 58 mm, respectively. Both study sites were composed of glaciofluvial deposits with silt loam to loamy sand textures with high coarse fragment content (MacKillop et al., 2018) and soils were classified as Orthic Dark Brown Chernozems; however, stoniness and moisture deficiency limit soil quality (BC Ministry of Agriculture and BC Ministry of Environment & Climate Change Strategy, 2018).

3.4.2 Study design

Two study designs were employed, one at Wycliffe, which included three grazing treatments (no grazing (control), grazing once annually, grazing twice annually), and one at

Table 3.1. Cover (mean ± SD) of the most common native and non-native grasses and forbs, native shrubs, and biological soil crust in May 2019 at Wycliffe and Tobacco Plains.

Group	Scientific Name	Common Name	Cover (%)
----- Wycliffe -----			
Native grasses	<i>Achnatherum nelsonii</i> (Scribn.) Barkworth	Columbia needlegrass	3.9 ± 3.8
	<i>Poa secunda</i> J. Presl	Sandberg's bluegrass	3.3 ± 4.1
	<i>Festuca idahoensis</i> Elmer	Idaho fescue	2.6 ± 4.6
Non-native grasses	<i>Poa pratensis</i> L.	Kentucky bluegrass	1.8 ± 2.5
	<i>Poa compressa</i> L.	Canada bluegrass	1.3 ± 2.2
Native forbs	<i>Lupinus sericeus</i> Pursh	silky lupine	4.6 ± 2.3
	<i>Potentilla arguta</i> Pursh	tall cinquefoil	2.9 ± 3.5
	<i>Achillea millefolium</i> L.	yarrow	2.4 ± 3.7
Non-native forbs	<i>Potentilla recta</i> L.	sulphur cinquefoil	13 ± 14
	<i>Taraxacum</i> spp.	dandelion	4.1 ± 4.4
	<i>Tragopogon dubius</i> Scop.	yellow salsify	2.3 ± 2.0
Native shrubs	<i>Rosa</i> spp.	rose	0.7 ± 1.6
Biological soil crust	-	-	1.9 ± 2.1
----- Tobacco Plains -----			
Native grasses	<i>Hesperostipa comata</i> (Trin. & Rupr.) Barkworth	needle-and-thread grass	5.8 ± 6.2
	<i>Poa secunda</i> J. Presl	Sandberg's bluegrass	3.7 ± 4.1
	<i>Koeleria macrantha</i> (Ledeb.) Schult.	junegrass	1.3 ± 1.9
Non-native grasses	<i>Bromus tectorum</i> L.	downy brome	4.5 ± 12
	<i>Poa compressa</i> L.	Canada bluegrass	2.9 ± 5.1
Native forbs	<i>Astragalus miser</i> Douglas ex Hook.	timber milk-vetch	2.1 ± 3.9
	<i>Arnica fulgens</i> Pursh	orange arnica	2.1 ± 2.9
	<i>Achillea millefolium</i> L.	yarrow	1.2 ± 2.1
Non-native forbs	<i>Potentilla recta</i> L.	sulphur cinquefoil	9.6 ± 8.7
	<i>Veronica verna</i> L.	spring speedwell	2.7 ± 2.8
Native shrubs	<i>Symporicarpos albus</i> (L.) S.F. Blake	common snowberry	0.0 ± 0.1
Biological soil crust	-	-	24 ± 18

Tobacco Plains, which included six treatments, of which three were grazing treatments (no grazing (control), grazing once annually, grazing twice annually), one was an herbicide treatment (one-time herbicide application), and two were grazing plus herbicide treatments (grazing once + herbicide, grazing twice + herbicide). As well, seeding with a native grassland species mix was applied with and without fertilizer (14-14-14, N-P-K) within each treatment at Tobacco Plains, excluding no grazing. Herbicide application and seeding were not conducted at Wycliffe as both management strategies were not permitted on the grassland.

Grazing treatments at each site were conducted in continuous 4 ha sections representing no grazing (control), grazing once, and grazing twice. Prior to grazing in May 2019, 8 permanent plots, 6 m² in dimension, were randomly distributed within each 4 ha section at Wycliffe (total = 24) and 16 permanent plots were randomly distributed within each 4 ha section at Tobacco Plains (total = 48). Half (8) of the grazed once, grazed twice, and ungrazed plots at Tobacco Plains were randomly selected for herbicide treatment. Map coordinates were used to locate the 6 m² treatment plots within each 4 ha section. Due to the patchy nature of the *P. recta* invasion, a 12 m radius plot at each treatment plot location was used to identify the most dense patch of *P. recta* and a permanent plot was established within the patch in order to capture treatment impacts on *P. recta*. Permanent plots were 30 to 100 m apart. Because the 8 experimental units per grazing treatment were grazed simultaneously by one herd of goats, neither study (Wycliffe nor Tobacco Plains) was replicated in space. Accordingly, statistical inferences for the grazing only treatments are limited to these two specific study sites and the grazing + herbicide treatments are limited to the Tobacco Plains study site. Statistical inferences for the control and herbicide treatments, however, were replicated in space and can be extended beyond the study sites.

A herd of Spanish goats, composed of 145 adults and 50 kids, at approximately 1,086 kg ha⁻¹ and 0.7 animal unit month (AUM) ha⁻¹, were used at both sites. Goats remained in the treatment area until 90% of *P. recta* buds, flowers, and seed heads were grazed. Utilization percentage was visually estimated. In 2019 and 2020, the first graze occurred during the *P. recta* pre-flowering stage (Tobacco Plains: June 1-6, 2019 and June 2-6, 2020; Wycliffe: June 7-13, 2019 and June 7-13, 2020) and the second graze occurred during the flowering and seedset stage (Tobacco Plains: July 6-7, 2019 and July 6-7, 2020; Wycliffe: July 10-11, 2019 and July 8-10, 2020). Grazing duration in 2019 and 2020 at Wycliffe was 4.1 hrs ha⁻¹ and 3.5 hrs ha⁻¹, respectively, during the first graze, and 2.1 hrs ha⁻¹ and 2.3 hrs ha⁻¹, respectively, during the

second graze. At Tobacco Plains, grazing duration was slightly less in both 2019 and 2020 at 3.7 hrs ha⁻¹ and 2.9 hrs ha⁻¹, respectively, during the first graze, and 1.6 hrs ha⁻¹ and 2.0 hrs ha⁻¹, respectively, during the second graze. Portable electric fencing, dogs, and herders were used to confine goats to each treatment section. Plots receiving herbicide at Tobacco Plains were sprayed with aminopyralid (Milestone®; Veseris, 5730 80 Avenue SE, Calgary, Alberta, Canada, T2C 4S6) using a backpack sprayer at a rate of 56 g ai ha⁻¹ on July 18, 2019, during the *P. recta* flowering and seedset stage. Application rate was just under half the maximum application rate for aminopyralid within grasslands (120 g ai ha⁻¹; Dow AgroSciences Canada Inc., 2021). Wind direction was southwest at a wind speed ranging from 20-28 km h⁻¹ and temperature was 17 °C. Seeding and fertilizing were conducted on Tobacco Plains in November 2019. In each 6 m² treatment plot, excluding the control, two 1 m² plots were established one meter from the bottom corners of the treatment plot. Seeding occurred in both plots and fertilizer was applied to one of the plots. Trials were unsuccessful and are not presented in the results. Detailed methods and results are presented in Appendix A.

Data and sample collection occurred from May 23-30, 2019, prior to treatment implementation; from July 23-28, 2019, following the first implementation of grazing and herbicide treatments; from May 21-30, 2020, prior to the implementation of the second year of grazing; and from July 21-27, 2020, after the second graze was completed. Percent cover was determined by ocular estimation to the nearest percent within a permanent 1 m² plot located 0.5 m from the top center in the 6 m² treatment plot. Voucher specimens of identified species were collected and are housed in the W.P. Fraser Herbarium at the University of Saskatchewan. Number of seed heads of *P. recta* was recorded in a 0.25 m by 0.5 m quadrat randomly placed in the 6 m² treatment plot, which was followed by sampling of aboveground biomass of *P. recta* and native and non-native forbs and grasses as well as soil from 0-10 cm within the same quadrat. Biomass samples were dried over 10-14 days at 40 °C and subsequently weighed. Soil was air dried and sieved through a 2 mm meshed sieve to remove roots and rocks.

Approximately 15 g of sieved soil from each soil sample were dried in a drying oven set at 105°C for approximately 48 hrs. Once dried, gravimetric water content was calculated. Soil pH was measured on a 1:2 soil-water mixture using a pH probe (Five Easy pH/mV Bench Meter, Mettler Toledo, USA). Soil anions and cations, including nitrate (NO₃⁻), phosphate (PO₄³⁻), sulphate (SO₄²⁻), chlorine (Cl⁻), ammonium (NH₄⁺), sodium (Na⁺), potassium (K⁺), magnesium

(Mg²⁺), and calcium (Ca²⁺), were measured by ion chromatography using the Dionex ICS-2000 Ion Chromatography System (Sunnyvale, CA). A subset of four soil samples collected in July 2019 were randomly selected from each treatment at Wycliffe and Tobacco Plains and were oven dried at 40°C for 48 hr and measured for total C, organic C, inorganic C, and total N by ALS Environmental (Saskatoon, SK) (see Appendix B for soil results).

3.4.3 Statistical analysis

All statistical analyses were conducted in R 4.0.3 (R Core Team, 2020) with a significance level of $\alpha < 0.05$. A mixed-effects general linear model (lmer function, lme4 package) was used per site to analyze the effects of treatment, month/year (July 2019, May 2020, July 2020), and a treatment-by-month/year interaction on *P. recta* aboveground biomass, number of *P. recta* seed heads, and aboveground biomass of native and non-native forbs and grasses. Plot was a random factor to account for repeated measures. A log +1 transformation was performed on biomass data and a square-root transformation applied to the number of *P. recta* seed heads to meet model assumptions. When the interaction of treatment and month/year was significant, multiple comparisons of least-squares means were conducted using the Holm-Sidak method (lsmeans function, lsmeans package, and cld function, multcomp package). A one-way ANOVA was performed per site on *P. recta* aboveground biomass data collected in May 2019 to examine differences between treatment plots prior to treatment implementation. A log +1 transformation was conducted on biomass data from Wycliffe to meet model assumptions. All biomass and seed head values presented in the results are raw means.

To evaluate potential differences in plant community composition between Wycliffe and Tobacco Plains, as well as identify any month/year (July 2019, May 2020, July 2020) effects, non-metric multidimensional scaling (NMDS; metaMDS function, vegan package) was used on Hellinger dissimilarity matrices of vegetation percent cover. An NMDS ordination with species vectors fitted to the ordination and significant at $p \leq 0.01$ was also conducted per study site to examine treatment effects on plant community composition. Permutational multivariate analysis of variance (PERMANOVA; adonis function, vegan package) was used to assess differences in plant community composition between the combined effects of site and month/year, and to identify differences in plant community between treatments per study site. The proportion of *P.*

recta and native and non-native grass and forb cover in July 2020 was also determined per treatment to observe treatment effects on each group per study site.

3.5 Results and Discussion

3.5.1 Impacts of targeted goat grazing and aminopyralid on *Potentilla recta*

Potentilla recta aboveground biomass and number of seed heads was reduced following targeted grazing at Wycliffe, and by the targeted grazing and herbicide treatments at Tobacco Plains. However, differences were not detected at all post-treatment time points (Table 3.2), which was in support of our hypothesis that treatment and season interactions would occur.

Table 3.2. ANOVA on linear mixed models of *Potentilla recta* aboveground biomass and number of seed heads from plots at Wycliffe and Tobacco Plains. Treatments at Wycliffe included control, grazing once per year over 2 years, and grazing twice per year over 2 years, and treatments at Tobacco Plains included control, grazing once per year over 2 years, grazing twice per year over 2 years, herbicide applied once, grazing once + herbicide, and grazing twice + herbicide. Month/Year within the biomass analysis included July 2019, May 2020, and July 2020 whereas Month/Year within the seed head analysis excluded May 2020 as seed heads were not present at this time. *Potentilla recta* aboveground biomass was log +1 transformed and number of seed heads was square-root transformed to meet model assumptions.

Attribute	Variable	Wycliffe		Tobacco Plains	
		df	F value (p value)	df	F value (p value)
<i>Potentilla recta</i> aboveground biomass	Treatment	2	21 (< 0.001)	5	9.8 (< 0.001)
	Month/Year	2	45 (< 0.001)	2	7.7 (< 0.001)
	Treatment x Month/Year	4	3.6 (0.014)	10	5.9 (< 0.001)
Number of <i>Potentilla recta</i> seed heads	Treatment	2	40 (< 0.001)	5	32 (< 0.001)
	Month/Year	1	1.6 (0.206)	1	36 (< 0.001)
	Treatment x Month/Year	2	3.3 (0.047)	5	18 (< 0.001)

At Wycliffe, *P. recta* aboveground biomass was lower in 2019 and 2020 following grazing once (pre-flowering) and grazing twice (pre-flowering and flowering/seedset) when compared to the control, with biomass reduced by 63% and 75%, respectively, in July 2019, and 56% and 76%, respectively, in July 2020 (Fig. 3.2a). In May 2020, prior to the second year of grazing, biomass did not differ between the control and grazing treatments, which was also observed in May 2019 before treatments were implemented. In July 2019, number of seed heads in both the grazing once and grazing twice treatments were lower than the control, with seed

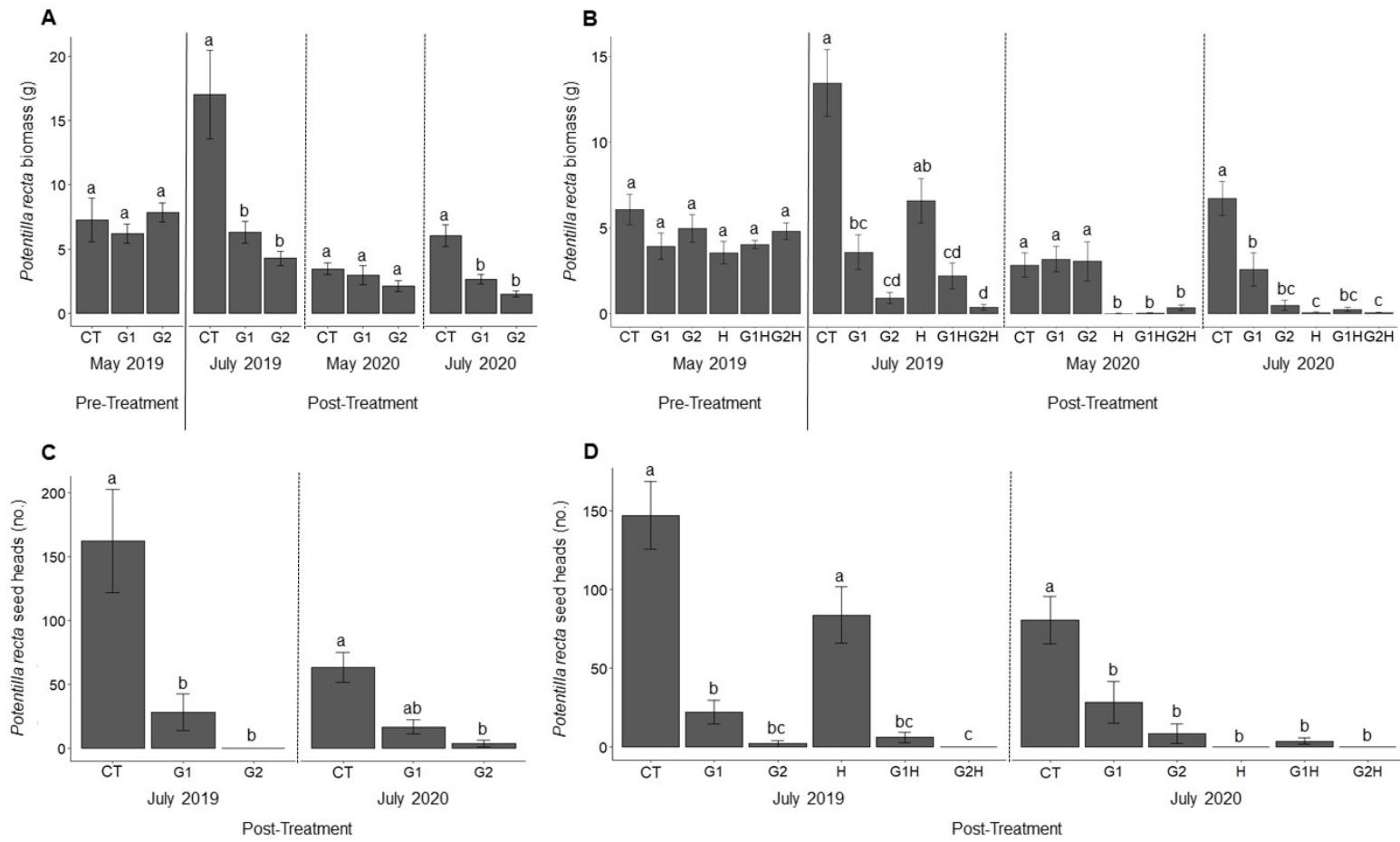


Figure 3.2. *Potentilla recta* aboveground biomass at Wycliffe (A) and Tobacco Plains (B) pre- and post-treatment, separated by month/year and treatment (CT: control, G1: grazing once per year over 2 years, G2: grazing twice per year over two years, H: herbicide applied once, G1H: grazing once + herbicide, G2H: grazing twice + herbicide). Number of *Potentilla recta* seed heads at Wycliffe (C) and Tobacco Plains (D) post-treatment, separated by month/year and treatment. Bars represent mean with standard error. Aboveground biomass and seed heads were influenced by a treatment-by-month/year interaction at both field sites ($p < 0.05$; ANOVA on linear mixed models). Comparisons between treatments within a given month/year are shown with different letters indicating significant differences.

heads reduced by 83% and 100%, respectively (Fig. 3.2c). However, in July 2020, number of seed heads were only lower in the grazing twice treatment in comparison to the control, with seed heads reduced by 94%. At Tobacco Plains, *P. recta* aboveground biomass and number of seed heads were also lower in 2019 and 2020 following grazing once and grazing twice treatments when compared to the control. In the grazing once and grazing twice treatments, biomass was reduced by 73% and 93%, respectively, in July 2019, and 62% and 93%, respectively, in July 2020 (Fig. 3.2b). Similar to Wycliffe, biomass did not differ between the control and grazing once and grazing twice treatments in May 2020, which was also observed in May 2019, prior to treatment implementation. Further, number of seed heads declined by 85% and 99%, respectively, in July 2019, following grazing once and grazing twice, and 65% and 89%, respectively, in July 2020 (Fig. 3.2d).

In our study, we did not measure *P. recta* stubble height directly following targeted grazing; however, the decline in *P. recta* aboveground biomass and number of seed heads in response to targeted grazing conducted once at pre-flowering and twice at pre-flowering and flowering/seedset is similar to the trend reported in a clipping study by Frost and Mosley (2012). *Potentilla recta* aboveground biomass and number of buds, flowers, and fruits declined when clipped to 7.5 cm, once at pre-flowering, and twice at pre-flowering and seedset, in both years of their study. When clipped to 15 cm, number of buds, flowers, and fruits declined following both treatments in each year, although aboveground biomass at pre-flowering did not differ from the control in one of the two years, which was a wetter year.

At both our field sites, the reduction in *P. recta* aboveground biomass and number of seed heads did not differ between the grazing once and grazing twice treatments in 2019 or 2020 (Fig. 3.2). This is contrary to our hypothesis that greater suppression of *P. recta* would be achieved with two grazing events rather than one. In years with seasonal climate conditions that support increased growth and reproduction of *P. recta*, there is greater opportunity for *P. recta* to recover if targeted grazing is only conducted once during pre-flowering, although seed viability is reduced (Frost and Mosley, 2012). Frost and Mosley (2012) found similar reductions in biomass and seed production when *P. recta* was clipped only once at flowering or at seedset compared to two “grazing” events. Similarly, Rinella, Jacobs, Sheley, and Borkowski (2001) found a single mowing of spotted knapweed (*Centaurea maculosa* Lam.) in the fall during the flowering or seed production stage reduced *C. maculosa* cover and density just as effectively as

repeated mowing. However, Mosley et al. (2017) documented no difference in the decline of *P. recta* buds, flowers, and seed heads following targeted sheep grazing applied once during the early flowering stage of *P. recta* and once during the late flowering-early seedset stage, nor was there a difference in the reduction of viable seeds. Further study is needed to examine whether the application of targeted goat grazing once during flowering or seedset effectively suppresses *P. recta* compared to two targeted grazing events. As well, whether *P. recta* recovery following targeted goat grazing at flowering or seedset is reduced compared to targeted goat grazing conducted once during pre-flowering.

The effects of aminopyralid at Tobacco Plains were demonstrated in 2020 with *P. recta* growth and seed head production reduced in all herbicide treatments (i.e., herbicide only, grazing once + herbicide, grazing twice + herbicide), with no differences between treatments (Figs. 3.2b and 3.2d). Herbicide effects were not documented in July 2019 as aminopyralid was applied a week prior to data collection, which was insufficient time for *P. recta* to respond to the herbicide. *Potentilla recta* aboveground biomass was reduced by 87-99% in May 2020 and 96-99% in July 2020 in all herbicide treatments, when compared to the control. Biomass did not differ between the grazing twice and herbicide treatments in July 2020; however, biomass was lower in the herbicide only and grazing twice + herbicide treatment compared to grazing once. Number of seed heads declined by 96-100% in July 2020 in all herbicide treatments, with no differences between the herbicide and targeted grazing treatments.

We hypothesized that the combined treatment of targeted goat grazing and aminopyralid would have the greatest efficacy in suppressing *P. recta*. The integration of targeted grazing and herbicide treatments has more effectively controlled invasive forbs compared to treatments applied alone. For example, Sheley et al. (2004) determined the integration of a spring 2,4-D application with repeated targeted sheep grazing was highly effective in reducing *C. maculosa* density, cover, and biomass within *C. maculosa*-infested rangelands. As well, Lym et al. (1997) found leafy spurge (*Euphorbia esula* L.) density was rapidly reduced and control was maintained longer when targeted goat grazing was combined with an annual fall application of picloram plus 2,4-D within an *E. esula*-infested grassland. In our study, there was no difference in the response of *P. recta* between herbicide treatments, suggesting an integrated targeted grazing and herbicide approach is not necessary to manage *P. recta* on grasslands within Tobacco Plains. In other

grasslands, an integrated targeted grazing and herbicide approach may be warranted based on variations in *P. recta* growth and reproduction in response to environmental conditions.

Herbicides used to control *P. recta* have included 2,4-D, dicamba + 2,4-D, 2,4-D + clopyralid, 2,4-D amine, metsulfuron-methyl, triclopyr, glyphosate, and picloram (Sheley and Denny, 2006; Endress et al., 2008). Endress et al. (2008, 2012) found picloram to be the most effective herbicide for suppressing *P. recta* within their study area, reducing *P. recta* cover by 90-95%, 80%, and 57% one, three, and six years post-treatment, respectively. Our study suggests aminopyralid is an additional herbicide that land managers may apply to control *P. recta*.

The reduction in *P. recta* aboveground biomass in May 2020 within the herbicide treatments demonstrates a soil residual effect one year following the one-time application of aminopyralid, even though just under half (56 g ai ha^{-1}) the maximum application rate (120 g ai ha^{-1}) of aminopyralid was applied. The decline in biomass also suggests an immediate re-treatment of aminopyralid is unnecessary. A longer-term study is needed to determine if an herbicide legacy can be achieved and to identify the reapplication frequency of aminopyralid to maintain *P. recta* control. As well, to determine if *P. recta* develops a resistance to aminopyralid if the herbicide is applied at half the application rate rather than the maximum application rate. In the targeted grazing only treatments, *P. recta* biomass did not differ between the control and targeted grazing only treatments at Wycliffe and Tobacco Plains in May 2020, suggesting re-treatment is required. However, a year following targeted sheep grazing, Mosley et al. (2017) reported a 41% and 47% reduction in *P. recta* yield when measured in June and July, respectively. In our study, a decline in biomass a year following targeted goat grazing may have been measured if *P. recta* biomass was assessed later in the growing season. Although yield was reduced a year following targeted sheep grazing, Mosley et al. (2017) suggests conducting targeted grazing for at least 5 years to reduce *P. recta* seed production, which inhibits the recruitment of *P. recta*. Additional research is needed to examine the grazing legacy attained by targeted goat grazing and identify the number of years targeted goat grazing should be conducted to inhibit *P. recta* recruitment as well as negatively affect the survival of established *P. recta* plants.

3.5.2 Impacts of targeted goat grazing and aminopyralid on the plant community

Plant community composition was different between sites with 23 of 50 species documented at Wycliffe not captured at Tobacco Plains, and 42 of 69 species identified at Tobacco Plains not recorded at Wycliffe. A PERMANOVA analysis identified a difference between the plant communities at Wycliffe and Tobacco Plains with a site-by-month/year interaction ($F_{2,210} = 5.77, p = 0.001$). Seasonal trends in native species richness were evident at both sites with richness higher in May compared to July. Reduction in richness was driven by a decline in native forbs, with native forb richness reduced by 28% and 55% in the control plots at Wycliffe and Tobacco Plains, respectively, from late May to late July due to mid-summer dormancy and senescence.

Treatments affected plant community composition at each site (PERMANOVA: Wycliffe, $F_{2,63} = 7.12, p = 0.001$; Tobacco Plains, $F_{5,126} = 5.24, p = 0.001$). In the NMDS analysis for Wycliffe and Tobacco Plains, the control plots separated from the treated plots, which was driven by higher *P. recta* cover in the controls (Figs. 3.3a and 3.3b). In addition to a reduction in *P. recta* cover, increasing native and non-native grass cover was observed in both the grazing and herbicide treatments. At Wycliffe, greater non-native grass cover, particularly Canada bluegrass (*Poa compressa* L.), in the grazing once treatment, and higher native grass cover, particularly Columbia needlegrass (*Achnatherum nelsonii* (Scribn.) Barkworth), in the grazing twice treatment, appear to be driving differences between grazing treatments and the control (Figs. 3.3a and 3.3c). At Tobacco Plains, native grass cover was notably higher in the herbicide only and grazing plus herbicide treatments compared to the control and grazing only treatments (Fig. 3.3d), which is in support of our hypothesis that herbicide treatments would result in more off-target effects and select for an increase in grass cover. Needle-and-thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth) and junegrass (*Koeleria macrantha* (Ledeb.) Schult.) appear to be the primary species contributing to this difference, particularly between the control and grazing twice + herbicide treatment (Fig. 3.3b). An increase in native grass biomass was also observed within the herbicide treatments in July 2020 (Appendix C). As well, non-native grass biomass was greater in the herbicide only and grazing once + herbicide treatments compared to the other treatments (Appendix C). Native forb cover did not show clear differences between treatments at either site. However, native forb biomass was significantly affected by treatment at Wycliffe ($p = 0.049$), particularly following two targeted grazing treatments, with

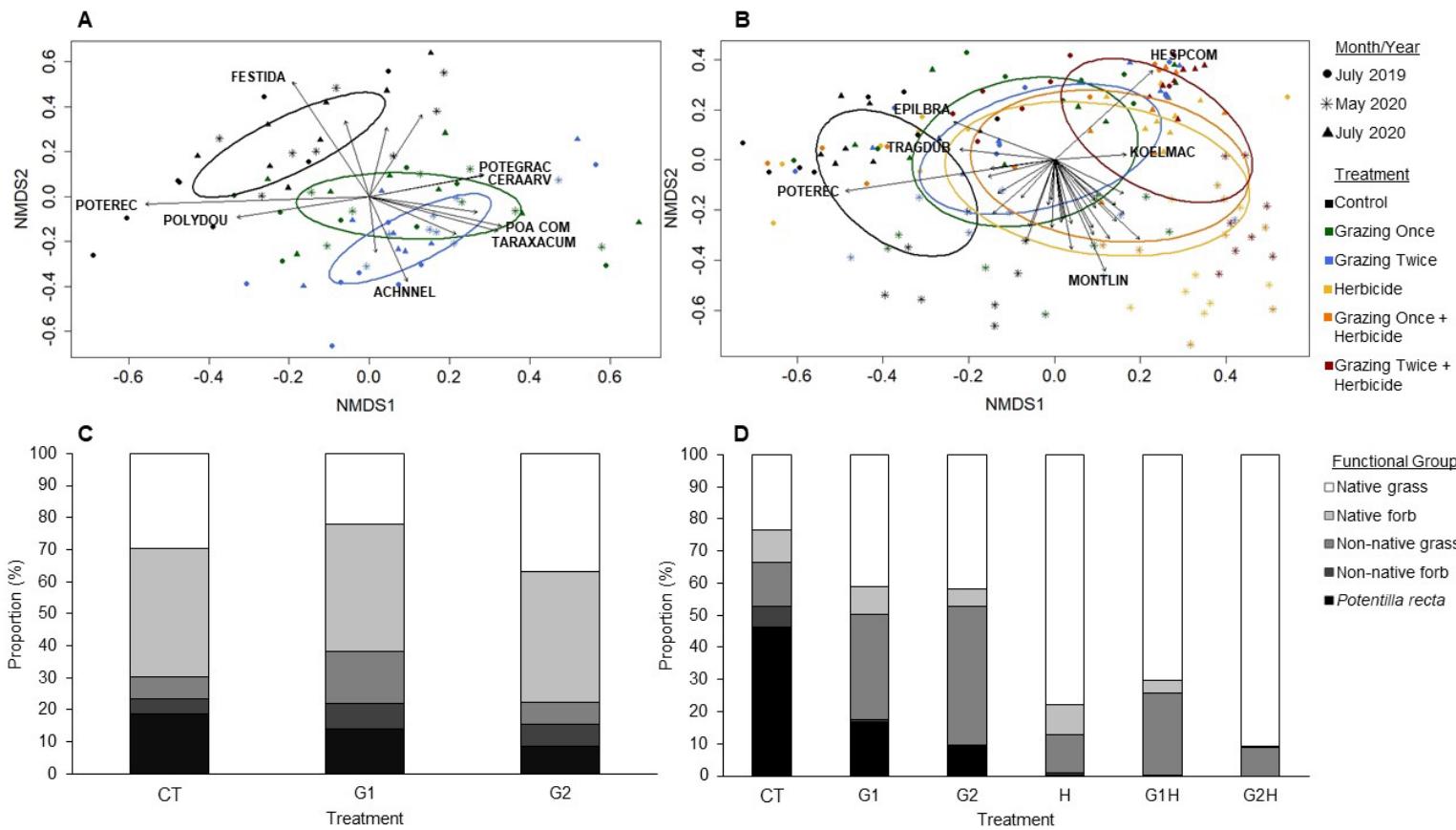


Figure 3.3. Non-metric multidimensional scaling (NMDS) ordination of vegetation percent cover at Wycliffe (A; $k = 3$, stress = 0.162) and Tobacco Plains (B; $k= 3$, stress = 0.123), separated by month/year and treatment. Species vectors (black arrows) were fitted to the ordination, significant at $P \leq 0.01$, with letter codes representing specific species (ACHNNEL, *Achnatherum nelsonii*; CERAARV, *Cerastium arvense* subsp. *strictum*; EPILBRA, *Epilobium brachycarpum*; FESTIDA, *Festuca idahoensis*; HESPCOM, *Hesperostipa comata*; KOELMAC, *Koeleria macrantha*; MONTLIN, *Montia linearis*; POA COM, *Poa compressa*; POLYDOU, *Polygonum douglasii*; POTEGRAC, *Potentilla gracilis*; POTEREC, *Potentilla recta*; TARAXACUM, *Taraxacum spp.*; TRAGDOB, *Tragopogon dubius*). Proportion of *Potentilla recta* and native and non-native forb and grass cover at Wycliffe (C) and Tobacco Plains (D) in July 2020, separated by treatment (CT: control, G1: grazing once per year over 2 years, G2: grazing twice per year over two years, H: herbicide applied once, G1H: grazing once + herbicide, G2H: grazing twice + herbicide).

biomass reduced in July 2019 and July 2020 by 96% and 46%, respectively, in the grazing twice treatment compared to the control (Appendix C).

Plant community shifts observed in our study align with others. Mosley et al. (2017) observed an increase in percent composition of perennial grasses a year following targeted sheep grazing of *P. recta* and sheep were reported to moderately consume forbs other than *P. recta*, with utilization of other forbs averaging 54%. Masin et al. (2018) recorded impacts to native forbs in response to targeted sheep grazing applied to manage non-native forbs, including *P. recta*, with 23% of the total forbs grazed representing native forbs. As well, other studies have reported an increase in grass cover following the application of broadleaf herbicides. Sheley and Denny (2006) observed an increase in perennial grass cover and biomass following the application of 2,4-D + clopyralid, 2,4-D amine, and picloram, and Endress et al. (2008) documented a shift from an exotic forb dominated system to an exotic grass dominated system in response to the application of picloram. In addition, declines in native forb cover and richness have been reported by others in response to the limited selectivity of broadleaf herbicides, altering plant community structure and function through reduced plant community diversity (Sheley and Denny, 2006; Ortega and Pearson, 2011; Skurski, Maxwell, & Rew, 2013).

Off-target effects of targeted grazing and herbicide treatments to native forbs is a particular concern expressed in studies managing *P. recta* (e.g., Sheley and Denny, 2006; Masin et al., 2018). To mitigate this risk at Wycliffe and Tobacco Plains, appropriate timing of targeted grazing is an important factor to consider as well as the application rate of herbicide. Native forbs were prevalent at Wycliffe and Tobacco Plains in early June, during the pre-flowering stage of *P. recta*; however, during the flowering and seed-set stage in early July, native forb richness declined due to mid-summer dormancy and senescence. A long-term study is needed to examine off-target effects of targeted goat grazing to native forbs and whether impacts are reduced if targeted grazing is applied in early to mid-July when *P. recta* is flowering and initiating seedset and native forbs are completing their lifecycle in response to summer drought.

Application of aminopyralid at the maximum rate for Milestone®, 120 g ai ha⁻¹ (Dow AgroSciences Canada Inc., 2021), presents the greatest risk to native forbs (Harrington et al., 2014). However, reducing the application rate of aminopyralid has potential to effectively suppress non-native dicots, such as *P. recta*, while lowering risks to native forbs (Harrington et al., 2014). In our study, aminopyralid was applied just under half the maximum application rate,

at 56 ai g ha⁻¹, and *P. recta* was suppressed with limited impacts to the native forb community. As well, Harrington et al. (2014) found the application of aminopyralid at 30 g ae ha⁻¹ reduced the abundance of non-native dicots with little impact to the abundance of native dicots and no detectable impact on native species richness. More research is needed to identify aminopyralid application rates and reapplication frequencies that will have limited impacts to the native forb community and effectively control *P. recta*, without *P. recta* developing a resistance to aminopyralid in response to a lower application rate.

3.5.3 *Potentilla recta* management in northern intermountain grasslands

Results from this study must be treated with caution, as our inference space was limited to our study areas. However, this study adds new information on *P. recta* management in grasslands by directly comparing targeted grazing and herbicide treatment efficacy and by being the first to examine *P. recta* management within grasslands in the intermountain region of Canada. Specifically, our study demonstrated that targeted goat grazing conducted once at the pre-flowering stage of *P. recta* or twice at pre-flowering and flowering/seedset achieved a similar reduction in *P. recta* aboveground biomass at each field site. A similar decline in number of *P. recta* seed heads was also achieved following both targeted grazing treatments, which reduces seed input into the soil seed bank. A one-time application of the herbicide, aminopyralid, at our Tobacco Plains field site effectively reduced *P. recta* aboveground biomass and number of seed heads one year following application, suggesting that yearly application of aminopyralid may be unnecessary due to the soil residual. A reduction in *P. recta* growth was not observed a year following targeted grazing treatments, which suggests yearly application of targeted goat grazing is required over multiple years to suppress *P. recta* growth and reproduction. Longer-term studies are needed to better understand the legacy of targeted goat grazing and aminopyralid treatments. In addition, both targeted goat grazing and aminopyralid application pose the risk of off-target effects, particularly to native forbs. This is important for land managers to consider and monitor as potential shifts in plant community composition in response to *P. recta* management may influence grassland recovery efforts.

4. ABOVEGROUND NATIVE PLANT BIOMASS REDUCES *POTENTILLA RECTA* GROWTH: THE ROLE OF A PRODUCTIVE NATIVE PLANT COMMUNITY TO MITIGATE REINVASION FROM THE SEED BANK OF INVADED NORTHERN INTERMOUNTAIN GRASSLANDS²

4.1 Preface

Revegetation is often considered an important component of invasive plant management to prevent reinvasion of the target invasive or secondary invasion by other invasive plants. Identifying plant communities that effectively suppress *P. recta* is important to establish communities that resist *P. recta* invasion. This chapter examines *P. recta* performance in native plant communities with varying functional groups to identify which communities may effectively suppress *P. recta*. Examination of the seed bank is also an important component of invasive plant management to determine the potential plant community that will establish following control of the invasive plant. This chapter examines the seed bank of northern intermountain grasslands to determine whether passive or active revegetation is necessary based on the representation of desirable species in the seed bank.

² This chapter was re-submitted for review to *Invasive Plant Science and Management* on March 18, 2022 as Juckers, M., Roozendaal, M. L., & Stewart, K. J. (2021). Aboveground native plant biomass reduces *Potentilla recta* growth: The role of a productive native plant community to mitigate reinvasion from the seed bank of invaded northern intermountain grasslands. Dr. Stewart assisted with developing the experimental designs, sample and data collection, and data analysis, and provided expertise to address major findings as well as editorial input. Marc Roozendaal conducted sample and data collection and performed the seed bank experiment. I developed the study design of the plant community experiment, with guidance from Dr. Stewart, conducted sample and data collection, completed the data analysis and interpretation, prepared the figure and tables, and completed the manuscript draft. Funding for this research was provided by the Columbia Basin Trust and the Fish and Wildlife Compensation Program.

4.2 Abstract

Sulphur cinquefoil (*Potentilla recta* L.) is an invasive plant of concern within grasslands in western North America. To better understand the role of native plant communities and soil seed bank in *P. recta* invasion within grasslands, we conducted two greenhouse studies to examine (1) *P. recta* growth response when grown with and without fertilizer in established native plant communities of varying functional groups (grasses, forbs, grasses and forbs), and (2) the existing prevalence of *P. recta* and other species in the soil seed bank at varying soil depths (0 to 5 cm, 5 to 10 cm, 10 to 15 cm) of grasslands invaded by *P. recta* in southeastern British Columbia, Canada. The growth response of *P. recta* did not differ between the native plant communities. However, *P. recta* above and belowground biomass declined as native plant aboveground biomass increased, suggesting a productive plant community may be important to suppress *P. recta*. Fertilizer did not affect the growth response of *P. recta* or native plants, suggesting nutrients may not have been a dominant limiting factor under greenhouse conditions. Nine species were identified in the soil seed bank. Seven were non-native, which included *P. recta*, and native species represented less than 2% of the seed bank. Of the average number of emerged non-native seedlings, over 20% were *P. recta*. Number of emerged *P. recta* seedlings was 69% lower at 10 to 15 cm compared to 0 to 5 cm soil depth, although the successful germination of *P. recta* at lower soil depths suggests viable *P. recta* seeds are persisting in the seed bank. Active revegetation may be an important strategy to mitigate *P. recta* reinvasion or secondary invasion by other invasive species from the soil seed bank.

4.3 Introduction

Grasslands are a defining characteristic of the intermountain region of the northwestern United States and southwestern Canada; however, anthropogenic practices, including fire suppression, agriculture, and overgrazing, have altered the disturbance regime of grasslands, leading to reduced ecological resiliency (Meyer, Callaham, Stewart, & Warren, 2021). Declines in ecological resiliency adversely affect a grassland system's ability to resist invasion, providing the opportunity for non-native species, such as sulphur cinquefoil (*Potentilla recta* L.), to invade and spread, altering the structure and function of native grassland communities (Endress et al., 2007; Meyer et al., 2021). This is demonstrated in the southern Rocky Mountain Trench of southeastern British Columbia, Canada, where heavy livestock grazing since the mid-1800s

shifted grassland communities from a system dominant in native bunchgrasses, including bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Love), Idaho fescue (*Festuca idahoensis* Elmer), and rough fescue (*Festuca campestris* Rydb.), to a system dominant in non-native species, including *P. recta* (Wikeem & Ross, 2002; Gayton, 2004).

Potentilla recta annually produces an average of 6,000 seeds per plant and seeds are primarily dispersed within three meters of the parent plant, which enables *P. recta* to form dense, continuous stands (Dwire et al., 2006). Seeds are dormant after maturity, with dormancy broken by a combination of soil moisture, exposure to light at the soil surface, and diurnal temperature fluctuations, after which seeds remain nondormant in the soil for over two years (Baskin & Baskin, 1990). Once seeds are brought to the soil surface and they are exposed to light, they can germinate throughout the growing season if soil moisture is nonlimiting (Baskin & Baskin, 1990). Baskin and Baskin (1990) found germination to be relatively high, ranging from 41-87% in the fall, following the after-ripening of seeds during the summer. Compared to its native congener, slender cinquefoil (*Potentilla gracilis* Dougl. ex. Hook.), McIver and Erickson (2012) found nearly twice as many *P. recta* seeds germinated (35.0% versus 19.5%) and seeds consistently germinated for over eight months following wetting, whereas the majority of *P. gracilis* seed germination occurred within two months following wetting. *Potentilla recta* also invested three times as much resources into seed production than *P. gracilis* and the proportion of buds that showed evidence of seed predation was only 0.01 compared to 0.22 for *P. gracilis*. The lack of seed predation, the input of seed into the seed bank and over two year viability of nondormant seeds in the soil, as well as the successful germination of *P. recta* over a long germination window, can allow *P. recta* to dominate both the seed bank and the aboveground plant community over time (Dwire et al., 2006). Generally, the abundance of seeds within a seed bank decreases with soil depth; however, an understanding of the seed bank at various soil depths is valuable because it determines whether the impact of an invasive plant, such as *P. recta*, is primarily at the surface layer, which is composed of the most recent seed rain, or whether its impact is on the more persistent component of the seed bank, which is present at a lower soil depth (Gioria & Pyšek, 2015). Seed banks depauperate in native species and dominated in *P. recta* and other non-native species can result in *P. recta* remaining dominant in the plant community or lead to secondary invasion from another invasive species (Mangold, 2012a).

Potentilla recta was identified by Ortega and Pearson (2005) as a ‘strong invader,’ which is an invasive plant that becomes dominant within a community at the expense of native species. Endress et al. (2007) attributed the success of *Potentilla recta* invasion to past land-use as *P. recta* dominance was found to be 37 times greater in old fields compared to less disturbed habitats, including grassland, shrubland, open forest, and forest. The study suggests *P. recta* dominance is primarily a result of the interaction between *P. recta* invasion, disturbance, and changes to land use/land cover rather than competitive superiority. As such, *P. recta* is suggested to be a “passenger” of fundamental environmental changes that are limiting native vegetation. However, research by Maron and Marler (2008a,b) found *P. recta* invasion into monocultures of native species significantly depressed native biomass and *P. recta* invasion into native plant communities reduced native biomass by an average of 22.1%. The studies by Maron and Marler indicate *P. recta* can successfully exert competitive dominance over native grassland species.

Although *P. recta* has demonstrated competitive dominance, certain native species, including tall cinquefoil (*Potentilla arguta* Pursh), common yarrow (*Achillea millefolium* L.), Wilcox’s penstemon (*Penstemon wilcoxii* Rydb.), and Idaho fescue (*Festuca idahoensis* ElmerElmer), exhibit resistance to *P. recta* invasion, with the greatest resistance exhibited by *P. arguta*, followed by *A. millefolium* (Maron & Marler, 2008b). Invasive forbs have been considered more functionally similar to native forbs than native graminoids, suggesting native forbs are key species in suppressing *P. recta* as they will directly compete with *P. recta* for resources in response to niche overlap (Funk, Cleland, Suding, & Zavaleta, 2008; Scharfy, Funk, Olde Venterink, & Güsewell, 2011). Maron and Marler (2008a) also found diverse plant communities were more resistant to *P. recta* invasion than less diverse communities, which aligns with the concept of limiting similarity in which a diversity of native species will ensure niche space is occupied that would otherwise be invaded (Funk et al., 2008). Funk et al. (2008) concluded a community that is more functionally diverse would eliminate or reduce available niches for invaders to occupy.

Potentilla recta control creates a disturbance in the plant community, which opens up niches available for colonization (Mangold, 2012a). Passive restoration, which relies on natural succession, is sufficient to fill the open niches if native plants are able to regrow quickly, there is an abundance of native plant propagules, and the disturbance created from *P. recta* control is low (Mangold, 2012a; Schuster, Wragg, & Reich, 2018). However, if the abundance of native species

is low in the existing plant community and seed bank, active revegetation is required (Mangold, 2012a). A literature review by Schuster et al. (2018) identified 85% of the grassland-based studies considered found revegetation reduced invasive plant performance, indicating revegetation in grasslands can effectively suppress invasive plants and limit reinvasion. As mentioned, a diverse plant community has been found to provide the greatest resistance to *P. recta* invasion (Maron & Marler, 2008a); however, Endress et al. (2012) found seeding with native grasses following herbicide application effectively reduced reinvasion of *P. recta* and the invasion of other undesirable species. A direct comparison of the resistance of native plant communities composed of grasses, forbs, or a combination of the two will provide further insight into revegetation efforts required to manage *P. recta* invasion. Further, manipulation of resource supply, specifically nutrients, will help determine if fertilization may aid revegetation efforts.

Fertilization has been used as a tool in invasive plant management to encourage the establishment and growth of desirable species through soil nutrient manipulation, increasing the potential for desirable species to outcompete invasive plants (Cole, King, Oyarzun, Dietzler, & McClay, 2007). However, the productivity and competitive response of the invader may also increase with greater resource availability (Davis, Grime, & Thompson, 2000). Maron and Marler (2008a, b) examined how increased resource supply would alter the competitive outcome of *P. recta* through a water supplemental treatment and found no effect of water addition on the competitive impact of *P. recta*. Examining *P. recta* response in fertilized plant communities will provide insight into whether fertilization increases *P. recta* productivity or whether it enhances native plant productivity to suppress *P. recta*, which supports the application of fertilization in revegetation efforts to manage *P. recta* invasion.

The purpose of this research was to gain insight into the role of native plant communities and soil seed bank in *P. recta* invasion within grasslands to aid grassland recovery efforts. Through two greenhouse studies we examined i) the above and belowground growth response of *P. recta* when grown with and without fertilizer in established native plant communities of varying functional groups, which included grasses, forbs, and grasses and forbs combined; and ii) the existing prevalence of *P. recta* and other species in the soil seed bank at varying soil depths (0 to 5 cm, 5 to 10 cm, 10 to 15 cm) of grasslands invaded by *P. recta* in southeastern British Columbia, Canada. We hypothesized *P. recta* suppression would be greatest in the forb only plant community and lowest in the grass only community and fertilizer application would

increase the growth response of both *P. recta* and native plants. We also hypothesized *P. recta* and other non-native species would dominate the soil seed bank but that the number of emerged seedlings from the seed bank would decrease with soil depth.

4.4 Materials and Methods

4.4.1 Study area

Soil and *P. recta* seed for the native plant community and soil seed bank studies were collected from grasslands on Tobacco Plains Indian Band (Yaqit ?a·knuqli ‘it) reserve ($49^{\circ} 4'57.44''\text{N}$, $115^{\circ} 5'59.68''\text{W}$), located within the East Kootenay Region of British Columbia, Canada, in the southern Rocky Mountain Trench (see Chapter 3, Fig. 3.1). Based on a rangeland assessment (Adams et al., 2016; Keefer Ecological Services Ltd., 2020), approximately 83% of grasslands on Tobacco Plains are unhealthy and 17% are healthy with problems. Native grasses, including needle-and-thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and Sandberg's bluegrass (*Poa secunda* J. Presl), and the non-native grass, Canada bluegrass (*Poa compressa* L.), are dominant within grasslands, while bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve) is present but sparse. *Potentilla recta* is a dominant non-native forb, with St. John's wort (*Hypericum perforatum* L.), yellow salsify (*Tragopogon dubius* Scop.), and spring speedwell (*Veronica verna* L.) common. Native forbs commonly found within the grasslands include *A. millefolium*, pussytoes (*Antennaria sp.*), and timber milk-vetch (*Astragalus miser* Douglas ex Hook.). Shrub cover (common snowberry (*Symporicarpos albus* (L.) S.F. Blake) and rose (*Rosa sp.*)) is sparse and ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) is encroaching. A biological soil crust layer is also common throughout these grasslands.

Grasslands in the East Kootenay region are characterized by very dry conditions and moisture deficits during the growing season (MacKillop et al., 2018). Average summer (April–September) and winter (October–March) season temperatures from 2010–2020 were $16 \pm 5.7^{\circ}\text{C}$ and $1.2 \pm 6.8^{\circ}\text{C}$, respectively (Eureka Ranger Station, MT, $48^{\circ}53'52.08''\text{N}$, $115^{\circ}3'51.84''\text{W}$). Average total precipitation during the summer and winter from 2010–2020 was $207 \pm 68\text{ mm}$ and $183 \pm 58\text{ mm}$, respectively. Grasslands are composed of glaciofluvial deposits with silt loam to loamy sand textures with high coarse fragment content (MacKillop et al., 2018). Soil is classified as Orthic Dark Brown Chernozem; however, stoniness and moisture deficiency influence soil

quality (BC Ministry of Agriculture and BC Ministry of Environment & Climate Change Strategy, 2018).

4.4.2 Native plant community greenhouse study

The native plant community greenhouse experiment was conducted from January to April 2020 to examine the growth response of individual *P. recta* plants grown with and without fertilizer within a plant community composed of i) native grasses, ii) native forbs, or iii) native grasses and forbs (Table 4.1). As the study was conducted in the greenhouse, results are limited in representing how *P. recta* growth would respond under field conditions. The experiment was arranged as a randomized factorial design with five replicates (n=30; 2 fertilizer levels x 3 community levels x 5 replicates). The grass and forb species selected are common native species in grasslands within the region (MacKillop et al., 2018), and some, specifically *F. idahoensis* and *A. millefolium*, exhibit resistance to *P. recta* invasion (Maron & Marler, 2008b). Historically, *P. spicata* was the dominant grass species within grasslands in the region and was therefore selected to represent the greatest portion of the seed mix in the grass only and forb and grass plant communities. *Achillea millefolium* was selected as the dominant forb species because of its resistance to *P. recta* invasion and current prevalence in grasslands throughout the region (Maron & Marler, 2008b; MacKillop et al., 2018).

Table 4.1. Proportion of grass and forb species in the native grass and/or native forb seeding treatments (native grasses = Grass, native forbs = Forb, both native grasses and forbs = Forb & Grass) within a greenhouse experiment. Seed was applied at a rate of 1,500 PLS m⁻², or 26 PLS per pot.

Scientific Name	Common Name	% of Seed Mix*		
		Grass	Forb	Forb & Grass
<i>Pseudoroegneria spicata</i> (Pursh) A. Löve	bluebunch wheatgrass	42	-	32
<i>Festuca idahoensis</i> Elmer	Idaho fescue	26	-	20
<i>Festuca campestris</i> Rydb.	rough fescue	19	-	15
<i>Koeleria macrantha</i> (Ledeb.) Schult.	junegrass	13	-	10
<i>Achillea millefolium</i> L.	yarrow	-	39	9
<i>Gaillardia aristata</i> Pursh	brown-eyed Susan	-	31	7
<i>Antennaria rosea</i> Greene	rosy pussytoes	-	30	7

* Percent based on number of PLS

Field soil was collected in July 2019 from a field site in the northern region of Tobacco Plains reserve (49° 4'17.89"N, 115° 7'18.64"W). Five locations at this site were randomly

selected, vegetation was removed, and soil was sampled to a depth of 30 cm to represent soils within the rooting zone of most plants. Collected soils were coarsely sieved to remove rocks and roots, and heated to 70°C for 40 minutes in an oven to thermally kill the seed bank (Dahlquist, Prather, & Stapleton, 2007). Potential changes in soil chemistry and biota in response to soil heating were not examined. *Potentilla recta* seed was collected in August 2018, at the same locations that soils were collected for the seed bank study described below. Seeds were collected from *P. recta* infested areas at 3 random locations within 3 grassland sites. At each collection location, seeds from a minimum of 75 mature seed heads were shaken into plastic bags and stored at 4°C until planting. Native seed was sourced in October 2019 (Green Patch Environmental Consulting Ltd., Edmonton, AB), as local seed was unavailable, and seed was stored at 4°C until planting. In January 2020, plastic pots (15 cm in top-diameter and 18 cm in height) were filled with a mixture of one part field soil and one part sand and saturated with water. Native grass and forb seeds, as well as fertilizer, where applicable, were dispersed on the soil surface and covered with a thin layer (0.5 cm) of soil. Seeding rate was 1,500 PLS m⁻², or 26 PLS per pot. The identity of the 26 PLS per pot was the same within each given plant community treatment. An N-P-K slow release fertilizer (TerraLink Horticulture Inc., Abbotsford, BC, Canada, V2S 7M1), at a formulation of 14-14-14, was applied at a rate of 10 g m⁻², or 0.18 g per pot. Pots were randomized on the greenhouse bench and were re-randomized once a week to account for potential differences in temperature, light, and humidity in the greenhouse. Pots were watered daily to prevent water stress. Daytime temperature of the greenhouse was 23°C and nighttime temperature was 19°C with a 17/7 hour light/dark cycle.

Native plant communities (grass, forb, and grass and forb) were seeded and grown for 5 weeks prior to transplanting four *P. recta* seedlings, which had been seeded and grown separately for two weeks, into each plant community. Cover in the grass, forb, and grass and forb plant communities after 5 weeks of growth averaged $42 \pm 7.5\%$, $56 \pm 9.9\%$, and $44 \pm 8.5\%$, respectively. The four *P. recta* seedlings were grown for two weeks within the plant communities, after which three of the four *P. recta* plants were removed. In each pot, the *P. recta* plant with the highest vitality was kept and where individuals had equal vitality, plants were selected randomly. The remaining *P. recta* plant grew within each experimental treatment for an additional 6 weeks and were harvested after a total of 10 weeks of growth, 8 of which were in each plant community. Following the 8-week period of *P. recta* growth in each plant community,

the aboveground biomass of native plants was collected. The height and lateral spread of each *P. recta* plant was measured and *P. recta* plants were subsequently removed from the pots.

Potentilla recta roots were washed to remove soil, measured to determine root length (i.e., longest root), and above and belowground biomass was separated. Native plant aboveground biomass and *P. recta* above and belowground biomass were dried over 10 to 14 days at 40°C and weighed.

4.4.3 Soil seed bank

Three sampling sites, located in the northern (49° 4'17.89"N, 115° 7'18.64"W), central (49° 2'12.08"N, 115° 7'13.05"W), and southern (49° 0'47.53"N, 115° 5'40.20"W) regions of Tobacco Plains reserve, were selected for soil seed bank analysis based on the widespread infestation of *P. recta* at each site. In late August 2018, three 30 cm by 30 cm soil pits were randomly dug at each site and soil was collected at 5 cm increments (0 to 5 cm, 5 to 10 cm, 10 to 15 cm) for a total of 27 samples (i.e., 3 locations x 3 sites x 3 depths). Soil was air dried and sieved through a 2 mm meshed sieve to remove roots and rocks. A 4 g subsample of soil from each sample was taken to measure ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), and potassium (K^+) concentrations by ion chromatography using the Dionex ICS-2000 Ion Chromatography System (Sunnyvale, CA). Remaining soil was stored in a -20°C freezer in darkness until further processing.

From October 2018 to February 2019, assessment of the soil seed bank was conducted using a greenhouse germination procedure. In the greenhouse, 134 g (~30%) of soil from each of the 27 soil samples collected in the field was mixed with 250 mL of potting mix (Sunshine Mix #4, Sun Gro Horticulture, Agawam, MA) and spread to a depth of 1 cm on plastic trays (34 cm by 21 cm by 12 cm). The soil mix was subsequently watered with 100 mL of water and trays were kept at a daytime temperature of 22°C and nighttime temperature of 17°C with a 17/7 hour light/dark cycle. Trays were watered twice daily to ensure optimal moisture conditions for seed germination. Over one month, emerged seedlings were identified to species, counted, and removed weekly. Unidentified seedlings were grown in trays for an additional week or transplanted to a pot and grown to maturity to assist with identification. Seedlings that emerged but died before identification were counted and classified as unknown forbs or grasses. Following one month, trays were air dried for three days, watered with 50 mL of water, and

subsequently cold stratified in a 4°C fridge for one month to break seed dormancy prior to returning to the greenhouse. In total, three germination-stratification cycles were conducted as this time frame was deemed sufficient for greater than 90% of seeds to germinate (Serajchi, 2017).

4.4.4 Statistical analysis

All statistical analyses were conducted in R 4.0.3 (R Core Team, 2020) with a significance level of $\alpha < 0.05$. A correlation analysis was conducted on *P. recta* above and belowground biomass, height, lateral spread, and root length to examine relationships between these response variables. Each variable was square root transformed to meet statistical assumptions. Analysis of covariance (ANCOVA) by the general linear model (GLM) was used to examine the effects of native plant community (grasses, forbs, grasses and forbs; fixed factor), fertilizer treatment (no fertilizer, fertilizer; fixed factor), total native plant aboveground biomass (covariate), and their interactions, on *P. recta* above and belowground biomass, height, lateral spread, and root length. A linear regression was also conducted to examine the relationship between total native plant aboveground biomass and each *P. recta* response variable. *Potentilla recta* above and belowground biomass were square root transformed to meet model assumptions of both the ANCOVA and linear regression. A significant interaction from the ANCOVA model was assessed by the function emtrends (emmeans package).

A two-way ANOVA was used to examine the effects of native plant community, fertilizer treatment, and their interaction, on total native plant aboveground biomass. A two-way ANOVA was also conducted per plant community to identify differences in aboveground biomass between native species as well as fertilizer effects. For this analysis, native species biomass was standardized by dividing biomass by the number of plants per species. Standardized biomass per plant community was square root transformed to meet model assumptions. Tukey's Honest Significant Difference test was conducted on significant model results.

The species identified from the soil seed bank were divided into the following groups: *P. recta*, other non-native forbs, native forbs, non-native grasses, and native grasses. A mixed-effects general linear model (lmer function, lme4 package) was conducted per group to evaluate potential differences in number of emerged seedlings between soil depths (0 to 5 cm, 5 to 10 cm, 10 to 15 cm). Grassland site (northern, central, southern) was considered a random factor to

account for site variability. A model was conducted per group due to poor model fit when all groups were included within a single model. To meet model assumptions, number of emerged seedlings was log +1 transformed and an outlier (+3 standard deviations) from the non-native forb group was removed. Significant model results were examined by multiple comparisons of least-squares means using the Holm-Sidak method (*lsmeans* function, *lsmeans* package, and *cld* function, *multcomp* package).

4.5 Results and Discussion

4.5.1 Native plant community greenhouse study

In our greenhouse study, *P. recta* above and belowground biomass, height, lateral spread, and root length were correlated ($r^2 > 0.80, p < 0.001$). The effect of the native grass, forb, and grass and forb plant communities on *P. recta* growth did not differ between the communities (Table 4.2). This was contrary to our hypothesis that *P. recta* suppression would be greatest in the forb only community and lowest in the grass only community. In a field study conducted by Larson et al. (2013), functionally similar species planted to suppress Canada thistle (*Cirsium arvense* (L.) Scop.) within a tallgrass prairie did not negatively affect the invasive plant, rather planted cool-season grasses and non-Asteraceae forbs reduced *C. arvense* cover. Larson et al. concludes the establishment of early and robust native species, regardless of functional similarity, is more resistant to *C. arvense* invasion than establishing a functionally diverse native plant community. Under greenhouse conditions, our study suggests establishing a plant community composed of either native grasses, forbs, or a mix of grasses and forbs can resist *P. recta* invasion; however, high biomass production may be critical to suppress *P. recta*.

Each *P. recta* variable was affected by native plant aboveground biomass (Table 4.2). The negative relationship was most pronounced with *P. recta* above and belowground biomass, with *P. recta* biomass declining as native plant biomass increased (Fig. 4.1). A significant interaction between total native plant aboveground biomass and plant community was identified for *P. recta* aboveground biomass (Table 4.2), with *P. recta* biomass lower in the forb only community compared to the grass only community (Fig. 4.1a). However, native plant biomass was higher in the forb only community (Table 4.3), which likely contributed to the lower *P. recta* aboveground biomass measured in this community. Greater invasive plant suppression and resistance to invasion has been associated with higher biomass production in other studies

Table 4.2. ANCOVA of the effects of native plant community (grasses, forbs, grasses and forbs; fixed factor), fertilizer treatment (no fertilizer, fertilizer; fixed factor), total native plant aboveground biomass (covariate), and their interactions, on *Potentilla recta* above and belowground biomass, height, lateral spread, and root length from a greenhouse experiment. *Potentilla recta* above and belowground biomass were square root transformed to meet model assumptions. *p* values below 0.05 are bolded.

Fixed Effects	Potentilla recta measurements									
	Aboveground biomass		Belowground biomass		Height		Lateral spread		Root length	
	F value	p value	F value	p value	F value	p value	F value	p value	F value	p value
Native Plant Community	1.26	0.309	0.46	0.639	0.42	0.663	1.96	0.170	1.39	0.274
Fertilizer Treatment	0.00	0.996	0.02	0.882	0.11	0.748	0.24	0.628	0.58	0.454
Total native plant aboveground biomass	32.8	<0.001	27.2	<0.001	8.46	0.009	18.1	<0.001	5.75	0.028
Native plant community x total native plant aboveground biomass	4.64	0.024	3.34	0.058	1.63	0.224	2.93	0.079	1.45	0.261
Fertilizer treatment x total native plant aboveground biomass	1.05	0.319	0.80	0.394	2.60	0.125	2.99	0.101	0.02	0.877
Native plant community x fertilizer treatment	0.47	0.631	0.47	0.632	0.55	0.584	0.40	0.676	1.06	0.369
Native plant community x fertilizer treatment x total native plant aboveground biomass	0.26	0.775	0.92	0.418	0.11	0.894	0.46	0.636	1.91	0.177

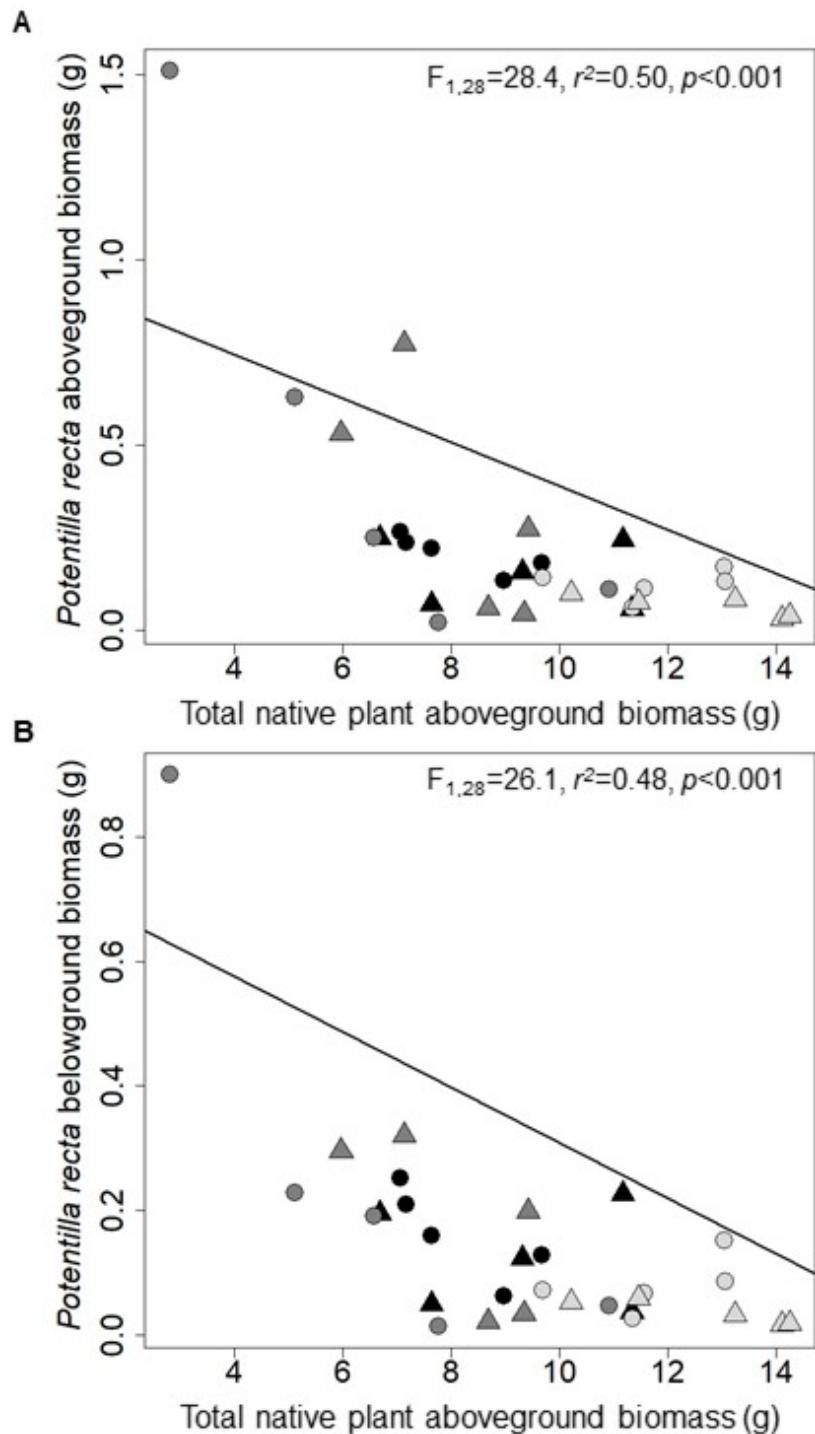


Figure 4.1. The relationship between total native plant aboveground biomass and *Potentilla recta* aboveground (A) and belowground (B) biomass in a greenhouse experiment. Triangles and circles represent data associated with fertilizer application and no fertilizer, respectively. Dark grey, light grey, and black represent data associated with the grass, forb, and grass and forb plant communities, respectively. The line represents the linear regression. The F , r^2 and p values obtained from the linear regression analysis are presented. Note the analysis was conducted on square-root transformed *Potentilla recta* above and belowground biomass.

Table 4.3. Aboveground biomass of each plant species (mean \pm SD), standardized by number of plants, and total aboveground biomass (mean \pm SD) per native plant community in a greenhouse experiment. Biomass was similar between fertilizer treatments ($p > 0.05$) and thus biomass presented is an average across fertilizer treatments per species and plant community. Different lowercase letters in the same column indicate significant differences in mean biomass between species ($p < 0.05$; ANOVA). Different uppercase letters in the total biomass row indicate significant differences in mean total biomass between plant communities ($p < 0.05$; ANOVA). Biomass of *Festuca idahoensis* and *Festuca campestris* were combined as differentiation between the two fescues was not determined.

Species	Native Plant Community		
	Grass	Forb	Grass and Forb
<i>Pseudoroegneria spicata</i>	0.535 \pm 0.265 ^a	-	0.347 \pm 0.195 ^b
<i>Festuca</i> spp.	0.303 \pm 0.061 ^{ab}	-	0.238 \pm 0.082 ^b
<i>Koeleria macrantha</i>	0.189 \pm 0.145 ^b	-	0.147 \pm 0.076 ^b
<i>Achillea millefolium</i>	-	1.038 \pm 0.291 ^a	1.131 \pm 0.723 ^a
<i>Gaillardia aristata</i>	-	0.173 \pm 0.081 ^b	0.215 \pm 0.162 ^b
<i>Antennaria rosea</i>	-	0.005 \pm 0.002 ^c	0.002 \pm 0.003 ^c
Total	7.378 \pm 2.383^B	12.21 \pm 1.573^A	8.673 \pm 1.693^B

(e.g., Sheley, Jacobs, & Svejcar, 2005; Maron & Marler, 2008a; Bybee-Finley, Mirsky, & Ryan, 2017; Möhrle, Reyes-Aldana, Kollmann, & Teixeira, 2021).

The inclusion of high biomass producing plants within a seed mix may be of importance to help resist *P. recta* reinvasion following *P. recta* control within invaded grasslands. In our study, *A. millefolium* had the greatest biomass production, representing an average of 85% and 54% of the biomass in the forb only and grass and forb plant communities, respectively (Table 4.3). *Pseudoroegneria spicata* followed, representing an average of 52% and 17% of biomass in the grass only and grass and forb only plant communities, respectively. Although our study found higher biomass production might be more important in *P. recta* suppression and resistance to invasion than plant community composition, Maron and Marler (2008a) found native plant diversity played a critical role in resisting *P. recta* invasion in their field study. Assemblages composed of higher species richness were less invaded and less impacted than assemblages with lower species richness. Assemblages with higher diversity were also associated with higher productivity.

Fertilizer did not affect *P. recta* (Table 4.2) or native plant aboveground biomass in our study (Table 4.3), which was contrary to our hypothesis that fertilizer application would increase the growth response of both *P. recta* and native plants. Grassland soils at Tobacco Plains are

generally nutrient poor. Ammonium and NO_2^- concentrations were below detection (1 ppm) and NO_3^- ($6.9 \pm 6.9 \mu\text{g g}^{-1}$) and PO_4^{3-} ($3.9 \pm 1.1 \mu\text{g g}^{-1}$) concentrations ranged from deficient to low, although K^+ concentrations ($21 \pm 26 \mu\text{g g}^{-1}$) ranged from moderate to sufficient (Flynn, 2015). Fertilizer addition was expected to increase nutrient availability, positively affecting plant growth. The lack of fertilizer effect suggests nutrient availability may not have been a dominant limiting factor. In a field study conducted by Maron and Marler (2007), soil moisture played a significant role in predicting spotted knapweed (*Centaurea stoebe* L.) invasion into experimentally assembled grass and forb plant communities. Under dry conditions, *C. stoebe* abundance was positively associated with deep soil moisture and NO_3^- , whereas under wet conditions, *C. stoebe* abundance was positively associated with light. Maron and Marler (2007) found water supplementation increased soil moisture as well as available N, which shifted competition for water and nutrients to competition for light. In our study, water was added to treatments to reduce water stress, which eliminated water as a limiting factor. In turn, light availability, rather than soil nutrients, may have become the dominant limiting factor, particularly for *P. recta*, as *P. recta* seedlings were introduced into established native plant communities. Nutrient leaching may have also occurred because of daily watering and nutrient release may have been limited because of the application of a slow-release fertilizer. Further, soils were heated (70°C for 40 minutes) prior to the experiment to thermally kill the seed bank, which may have altered the soil chemistry and biota influencing the observed fertilizer response.

In our study, conditions in the greenhouse were optimal for growth. In addition to nutrients, water is a limiting factor within grasslands on Tobacco Plains, which occur within a very dry climatic subregion of British Columbia (MacKillop et al., 2018). Research comparing the effects of native grass, forb, and grass and forb plant communities on *P. recta* growth is needed under dry climatic conditions. Further, the influence of fertilizer on these native plant and *P. recta* communities under typical dry field conditions should be examined.

4.5.2 Soil seed bank

From our soil seed bank analysis, nine species were identified, including five annuals and four perennials (Table 4.4). Seven of the species were non-native, of which two were monocots and five were dicots, which included *P. recta*. Non-native species represented approximately

Table 4.4. Scientific name, common name, plant family, and life cycle (A: Annual, P: Perennial) of seedlings that emerged from the soil seed bank using a greenhouse germination procedure from soils collected on Tobacco Plains.

Scientific Name	Common Name	Family	Life Cycle
Non-Native Forbs			
<i>Arenaria serpyllifolia</i> L.	thyme-leaved sandwort	Caryophyllaceae	A
<i>Capsella bursa-pastoris</i> (L.) Medik.	shepherd's purse	Brassicaceae	A
<i>Hypericum perforatum</i> L.	common St. John's-wort	Clusiaceae	P
<i>Myosotis stricta</i> Link ex Roem. & Schult.	blue forget-me-not	Boraginaceae	A
<i>Potentilla recta</i> L.	sulphur cinquefoil	Rosaceae	P
Non-Native Grasses			
<i>Bromus tectorum</i> L.	Cheatgrass	Poaceae	A
<i>Poa compressa</i> L.	Canada bluegrass	Poaceae	P
Native Forbs			
<i>Microsteris gracilis</i> (Hook.) Greene	pink twink	Polemoniaceae	A
Native Grasses			
<i>Festuca idahoensis</i> ElmerElmer	Idaho fescue	Poaceae	P

60% of the average total number of emerged seedlings from the soil seed bank (Table 4.5). Of the average number of emerged non-native seedlings, just over 20% were *P. recta*. *Festuca idahoensis* and pink twink (*Microsteris gracilis* (Hook.) Greene) were the only native species identified (Table 4.4), representing less than 2% of the number of emerged seedlings from the soil seed bank (Table 4.5). These findings support our hypothesis that non-native species, including *P. recta*, would dominate the seed bank of these grasslands. The composition of the seed bank aligns with the general observation made by Rice (1989) that grassland seed banks appear to be more developed in annuals than perennials, have a larger number of forbs than grasses, and are common in weedy species. In invaded systems, a depauperate seed bank is also a common observation (Clements & Atwood, 2012; Gioria et al., 2012; Rice, 1989). In our study, species richness in the soil seed bank was particularly low, although several emerged seedlings from the seed bank were unidentified (Table 4.5). As well, a limited number of soil samples were collected and a small portion of soil was analyzed, which may have also contributed to the low species richness.

The number of *P. recta* emerged seedlings from the soil seed bank was lower at 10 to 15 cm soil depth compared to 0 to 5 cm ($p = 0.013$), with a 69% reduction in emerged seedlings (Table 4.5). The number of emerged non-native grass seedlings also declined with depth ($p = 0.002$), with emerged seedlings reduced by an average of 59% from 0 to 5 cm to 5 to 10cm

Table 4.5. Number (mean \pm SD) of emerged seedlings in the soil seed bank per species in depth 0 to 5, 5 to 10 and 10 to 15 cm and in total (0 to 15 cm) in a greenhouse germination procedure from soils collected on Tobacco Plains. Replicates per soil depth, n=9. *Potentilla recta* and non-native grasses had higher mean number of emerged seedlings at 0 to 5 cm depth (different lowercase letters indicate significant differences, $p < 0.05$; ANOVA). Total number of emerged seedlings of non-native forbs, excluding *Potentilla recta*, and native grasses did not differ between soil depths. Number of emerged native forb seedlings was not compared between soil depths due to poor model fit.

	Mean number of emerged seedlings			
	Total	0-5 cm	5-10 cm	10-15 cm
Non-native forbs				
<i>Potentilla recta</i>	9 \pm 9	16 \pm 12 ^a	6 \pm 2 ^{ab}	5 \pm 4 ^b
<i>Arenaria serpyllifolia</i>	2 \pm 3	4 \pm 3	1 \pm 2	1 \pm 1
<i>Capsella bursa-pastoris</i>	11 \pm 10	16 \pm 13	9 \pm 8	9 \pm 10
<i>Hypericum perforatum</i>	0 \pm 1	0 \pm 1	0 \pm 1	0 \pm 0
<i>Myosotis stricta</i>	3 \pm 5	6 \pm 7	2 \pm 2	2 \pm 3
Total (excluding <i>P. recta</i>)	16 \pm 15	25 \pm 17	12 \pm 11	12 \pm 12
Non-native grasses				
<i>Bromus tectorum</i>	1 \pm 2	3 \pm 4	0 \pm 1	1 \pm 1
<i>Poa compressa</i>	13 \pm 15	20 \pm 17	11 \pm 16	8 \pm 10
Total	14 \pm 16	23 \pm 17 ^a	11 \pm 16 ^b	8 \pm 11 ^b
Native Forbs				
<i>Microsteris gracilis</i> *	0 \pm 0	0 \pm 0	0 \pm 0	0 \pm 0
Native Grasses				
<i>Festuca idahoensis</i>	1 \pm 2	1 \pm 2	1 \pm 1	0 \pm 1
Unknown species				
Forbs	25 \pm 24	42 \pm 30	21 \pm 20	11 \pm 8
Grass	2 \pm 2	3 \pm 2	2 \pm 1	2 \pm 4

* only one emerged seedling of *Microsteris gracilis* was identified at 5 to 10 cm soil depth within the southern field sit

and 10 to 15 cm soil depth. A decline in emerged seedlings was not measured for other non-native forbs and native grasses (other non-native forbs: $p = 0.113$; native grasses: $p = 0.603$) and the native forb, *M. gracilis*, was only identified at the 5 to 10 cm soil depth. This did not support our hypothesis that the number of emerged seedlings from all groups would decline with soil depth. The greater number of *P. recta* emerged seedlings from the 0 to 5 cm soil depth was likely attributable to recent seed rain. However, the successful germination of *P. recta* seeds from the lower soil depths suggests viable *P. recta* seeds are persisting in the seed bank.

The poor representation of native species within the soil seed bank from 0 to 15 cm suggests the seed bank is degraded and/or depleted. However, we acknowledge that by selecting areas of *P. recta* invasion within our grassland sites, we may have biased our seed bank analysis

towards invasion. Our study captured a snapshot of the soil seed bank in these invaded areas. Due to the spatial and temporal variability of seed banks, larger sampling areas with multiple sampling periods are needed to gain a more comprehensive picture of the extent of seed bank degradation and/or depletion (Gioria & Pyšek, 2015). As well, inclusion of a reference site would allow for a comparison of the seed bank in invaded versus uninvaded grasslands. Our study may have also underestimated viable seeds as different species depend on varying responses to light, temperature, oxygen availability, and moisture to germinate (Baskin & Baskin, 1989; Simpson, Leck, & Parker, 1989). Reviewing seed dormancy and germination requirements will help improve the seed bank analysis to better estimate species richness and density (Baskin & Baskin, 2014).

4.5.3 The soil seed bank and revegetation

Efforts to control *P. recta* within grasslands can create an open niche within the plant community (Mangold, 2012a). Our soil seed bank study revealed the seed bank at our grassland sites is dominated by *P. recta* and other non-native species, which indicates *P. recta* may reestablish within open niches created following *P. recta* control or secondary invasion by other non-native species may occur (Kettenring and Adams, 2011; Mangold, 2012a). The introduction of native plant propagules through active revegetation is needed to establish a plant community that prevents *P. recta* reinvasion or colonization and expansion of other non-native species from the seed bank (Kettenring and Adams, 2011).

Our native plant community greenhouse study suggests establishing a productive plant community may be important to resist *P. recta* reinvasion. Inter and intraspecific competition were not directly examined in our study and would provide more insight into the selection of species for revegetation. In addition, findings from Maron and Marler (2008a) indicate a diverse plant community provides significant resistance to *P. recta* reinvasion. Further research that applies a similar field study design to Larson et al. (2013) will provide insight into whether revegetating with highly productive species is more effective at preventing *P. recta* reinvasion than revegetating with a species rich seed mix (Mangold, 2012a).

5. SYNTHESIS AND CONCLUSIONS

Potentilla recta is an invader of serious concern within grasslands in the semi-arid intermountain region of the northwestern United States and southwestern Canada. A primary concern associated with the invasive success of *P. recta* is its broad ecological amplitude enabling it to invade a wide range of sites (Rice, 1999; Naylor et al., 2005). Despite its wide ecological range, disturbance is considered a primary factor facilitating *P. recta* invasion within plant communities (Endress et al., 2007). *Potentilla recta* has also demonstrated competitive superiority over several grassland plants native to North America (Maron & Maron, 2008b). Research on *P. recta* management has occurred in the northwestern United States. However, the establishment and spread of *P. recta* in British Columbia, Canada is of growing concern, particularly within southeastern British Columbia where a history of overgrazing by livestock and wild ungulates has increased the susceptibility of grasslands to *P. recta* invasion (Wikeem, Ross, and Newman, 2012). To address this concern, the primary goal of this study was to gain a better understanding of *P. recta* management within intermountain grasslands of southeastern British Columbia.

5.1 Principal Findings

5.1.1 Goat grazing and aminopyralid

The aim of this study was to identify management strategies that suppress *P. recta* within degraded intermountain grasslands in southeastern British Columbia. Specifically, we examined the efficacy of using: i) targeted goat herbivory to graze *P. recta* once annually, during the pre-flowering stage, versus twice annually, during pre-flowering and flowering/seedset; ii) aminopyralid as a one-time herbicide treatment; and iii) integrated targeted goat grazing and aminopyralid application versus targeted goat grazing and aminopyralid application alone. Treatment effects on plant community composition and the interaction between treatments and seasonality (spring and summer) were also assessed. Studies have examined control of *P. recta*

through herbicide (Sheley & Denny, 2006; Endress et al., 2008) and targeted grazing using sheep (Mosley et al., 2017; Masin et al., 2018); however, the efficacy of the application of aminopyralid and goat grazing has not been investigated and a comparison of the two treatment options has not been assessed.

The primary results from Chapter 3 indicate both targeted goat grazing and aminopyralid application can control *P. recta*, with reductions in growth and reproduction achieved. Declines in growth and reproduction did not differ between the grazing once and grazing twice treatments. However, the risk of *P. recta* recovery is greater following a single grazing event conducted during pre-flowering, particularly in years with seasonal climate conditions that support increased growth and reproduction. The window of time for *P. recta* to recover is decreased when a single grazing event is applied during flowering and seedset and thus the need for a second grazing event may not be required. In May 2020, prior to the second year of grazing, significant reductions in *P. recta* growth were measured in the herbicide only and grazing + herbicide treatments, with no difference between treatments. This indicates an integrated approach of targeted goat grazing and aminopyralid application may not achieve greater suppression of *P. recta* compared to aminopyralid application on its own. The successful suppression of *P. recta* one year following aminopyralid application suggests an herbicide legacy was achieved, indicating an annual application of aminopyralid is not required. A reduction in *P. recta* growth was not measured in the grazing only treatments prior to the second year of grazing, suggesting a grazing legacy was not attained. Annual grazing over multiple years may be required to prevent *P. recta* reproduction and to suppress *P. recta* growth. Although targeted goat grazing and aminopyralid application can control *P. recta*, both treatments pose the risk of off-target effects as increased grass cover was observed within these treatments. Shifts in plant community composition in response to *P. recta* management need to be considered by land managers as this will influence grassland recovery.

5.1.2 Native plant communities and seed bank

The aim of this study was to gain insight into the role of native plant communities and soil seed bank in *P. recta* invasion within grasslands to aid grassland recovery efforts. Two greenhouse studies were conducted to examine i) the above and belowground growth response of *P. recta* when grown with and without fertilizer in established native plant communities of

varying functional groups, which included grasses, forbs, and grasses and forbs combined; and ii) the existing prevalence of *P. recta* and other species in the soil seed bank at varying soil depths (0 to 5 cm, 5 to 10 cm, 10 to 15 cm) of grasslands invaded by *P. recta* in southeastern British Columbia. Studies have examined the efficacy of suppressing *P. recta* by individual native grassland species and native plant communities composed of a diversity of grasses and forbs; however, differences in *P. recta* suppression within a native grass, forb, and grass and forb plant community has not been compared. As well, to our knowledge, seed bank assessments have not been applied to research programs examining *P. recta* control within grasslands despite the value of seed bank assessments in identifying invasive plant dominance and the prevalence of non-native and native species, which will help determine the degree of revegetation efforts to be undertaken.

The primary results from Chapter 4 indicate that under greenhouse conditions, the growth response of *P. recta* did not differ between the native grass, native forb, and native grass and forb plant communities. However, *P. recta* growth declined as native plant aboveground biomass increased, suggesting the establishment of a productive plant community may be important to resist *P. recta* invasion. Fertilizer did not influence *P. recta* growth response, suggesting nutrients were not limiting under greenhouse conditions. Water was also added to plant communities to reduce water stress, which removed water as a limiting factor. As such, light availability may have become the dominant limiting factor influencing *P. recta* performance. The seed bank was species poor in comparison to the aboveground plant community and dominated by non-native plants, including *P. recta*, suggesting a degraded and/or depleted seed bank. *Potentilla recta* germinated seeds significantly declined from 0-5 cm to 10-15 cm soil depth; however, the successful germination of *P. recta* seeds from the lower soil depths suggests viable *P. recta* seeds are persisting in the seed bank. Control of *P. recta* through targeted grazing and herbicide application can create a disturbance within the plant community, which opens up available niches for colonization (Mangold, 2012a). The degraded state of the seed bank suggests active revegetation needs to be considered in management plans to mitigate *P. recta* reinvasion or secondary invasion by other invasive plants following *P. recta* control.

5.2 Management Implications

Goat grazing and the application of the herbicide, aminopyralid, are two management strategies that can be implemented by land managers to control *P. recta* within our study region

by reducing *P. recta* growth and reproduction; however, treatment selection depends on several factors. Although herbicide application is a frequently used practice in invasive plant management, lack of social acceptance is a common issue that must be considered when planning *P. recta* management initiatives. This was an issue during the initiation of our study, which led to herbicide application only occurring on one of the two study sites. As well, treatment selection may be impacted by cultural concerns, such as off-target effects on traditional plants. For example, one of our study sites occurred on the reserve lands of Tobacco Plains Indian Band and the traditional plant, bitterroot (*Lewisia rediviva* Pursh), is harvested in the area. Herbicide may adversely affect *L. rediviva*, which is a concern of community members. Targeted goat grazing is an alternative strategy with less risk to *L. rediviva* as it is a small, low-lying perennial herb that is unimportant forage to large herbivores (Howard, 1993). Management of grasslands on First Nations reserves and Indigenous traditional territories requires researchers and land managers to engage in collaborative research and land management with First Nations. As part of this research, I worked with the Lands and Resources Manager of Tobacco Plains Indian Band to initiate the research study, created memos to inform community members of the study, gave presentations, facilitated a community event, and partook in a four-month internship within the Lands and Resources Department (Appendix D).

Proximity to sensitive areas, such as water bodies, can effect treatment selection. In British Columbia, herbicide cannot be applied within 10 m of the high water mark, in accordance with the *Integrated Pest Management Act and Regulation*. Within this pesticide free zone, targeted goat grazing can be applied to control *P. recta* infestations. The risk of disease transmission from domestic goats to wildlife, particularly bighorn sheep (*Ovis canadensis* (Shaw)) and mountain goats (*Oreamnos americanus* Blainville), is a critical issue that must also be considered within our study region (Garde et al., 2005; Wild Sheep Working Group, 2012). In the Kootenay Region of southeastern British Columbia, domestic sheep and goat grazing are prohibited within 15 km of occupied or historic *O. canadensis* habitat (Poole & Ayotte, 2019). This impacted our study as an *O. canadensis* population occurs within 15 km of Tobacco Plains Indian Reserve. Discussions were held with Wildlife Biologists from the Ministry of Forest, Lands, Natural Resource Operations and Rural Development regarding the risk of targeted goat grazing on reserve lands. From these discussions, a decision was reached to constrain our study to the grassland in the northern reach of the reserve, which was furthest from the *O. canadensis*

population, to mitigate the risk of disease transmission. Further, management costs need to be examined as control of *P. recta* is a long-term process. Land managers must consider total area to be treated and treatment frequency. Our study suggests that yearly application of aminopyralid may be unnecessary because of the soil residual of the herbicide; however, annual targeted goat grazing may be required over several years to suppress *P. recta* growth and reproduction, which will affect treatment cost.

Both treatment options pose the risk of off-target effects, particularly to native forbs, which can adversely affect plant community structure and function. As well, aminopyralid application and targeted goat grazing treatments can create open niches within the plant community (Mangold, 2012a). Native plants may fill these open niches if they are well represented in the soil seed bank; however, as demonstrated in our study, *P. recta* and other non-native species may dominate the seed bank. This poses the risk of *P. recta* reinvading open niches created by control efforts or secondary invasion by other invasive plants (Kettenring & Adams, 2011; Mangold, 2012a). Despite efforts to control *P. recta*, off-target effects from management treatments and a degraded seed bank can sustain an undesirable plant community. A key goal of invasive plant management is identifying and establishing a desirable plant community that is resistant to future invasions (Masters & Sheley, 2001). Once a desirable plant community is identified, land managers need to assess how off-target effects and a degraded seed bank may influence the achievement of the desired plant community and ways to mitigate these impacts.

Timing of targeted grazing and herbicide application rate are important factors to consider to mitigate off-target effects. In response to summer drought, several native grassland species, particularly native forbs, complete their life cycle in July, which was observed in our study; however, *P. recta* continues to grow. Implementing targeted grazing in early to mid-July while *P. recta* is flowering and initiating seedset can reduce impacts to desirable native species. The risk of aminopyralid to native forbs may be reduced by decreasing the application rate. Our study and research by Harrington et al. (2014) have shown a reduced application rate can suppress *P. recta*, with limited impact to native forbs. However, the potential risk of *P. recta* developing a resistance to aminopyralid in response to the lower application rate must be considered. Active revegetation is also important to address off-target effects, mitigate *P. recta* reinvasion or secondary invasion by other invasive plants from the soil seed bank, and achieve a

desired plant community. As demonstrated through our greenhouse study, establishing a productive plant community shows potential to resist *P. recta* reinvasion. Although revegetation is an important component of invasive plant management, it is often met with limited success (Kettenring & Adams, 2011). In our study, a fall seeding of native grasses and forbs was conducted in early November at the Tobacco Plains field site. However, in the spring of the following year, seeded plots were examined and germination success was found to be poor or unsuccessful (Appendix A). Physiological, logistical, and ecological-environmental factors are linked to seeding failure, such as low seed viability, limited emergence, seed mix handling and delivery challenges, and variable environmental conditions (Pedrini et al., 2020). In our study, freezing and thawing of the seedbed prior to snowfall was likely a primary contributor to poor seedling recruitment (James, Svejcar & Rinella, 2011). Working with grassland ecologists and scientists on seed mix development and implementation will help land managers improve seedling recruitment success and achieve the desired plant community. Incorporating an ecologically based, holistic approach, such as the ecologically based, invasive plant management (EBIPM) framework, will also help guide management planning and implementation to successfully establish a desired plant community (Sheley & Smith, 2012).

The EBIPM framework applies the three causes of succession, including site availability (open niches for species establishment), species availability (seed availability to occupy open niches), and species performance (optimal resource levels for plant growth and reproduction) as well as the ecological processes linked with these causes (Mangold, 2012b; Sheley & Smith, 2012). The framework assesses the ecological processes that facilitated degradation, identifies treatments to manipulate succession to achieve a desirable plant community, and adaptively manage as needed. Targeted grazing and herbicide treatments can be used to manipulate site availability through control of *P. recta*. Species available to establish within open niches created through *P. recta* control can then be manipulated through seeding. Seeding can be done in stages to manage off-target effects on native forbs from *P. recta* management. Grasses can be seeded initially to fill ecological space and forbs can be subsequently inter-seeded once *P. recta* is sufficiently controlled, or forb islands can be established to eliminate potential competition between grasses and forbs and enable follow-up management of *P. recta* (Mangold, 2012a). Follow-up management will be required to ensure species performance of seeded species is successful and performance of *P. recta* and other undesirable species continue to be reduced, as

needed, through targeted grazing or herbicide treatments. Grassland recovery is a long-term process. Applying a framework such as EBIPM can guide land managers in rebuilding the structure and function of the plant community while controlling *P. recta*.

5.3 Future Direction

Potentilla recta is considered a strong invader that successfully outcompetes native plants and thrives in disturbed conditions (Ortega & Pearson, 2005; Endress et al., 2007; Maron & Marler, 2008b). In comparison to its native congener, graceful cinquefoil (*Potentilla gracilis* Douglas ex Hook.), *P. recta* seed production is greater with approximately twice as many seeds successfully germinating (McIver & Erickson, 2012). As well, seeds germinate over a longer period. This longer residency of viable seed in the environment may enable *P. recta* to rapidly populate disturbed habitats. Further, once *P. recta* is established, it can perpetuate itself (Perkins et al., 2006). Although *P. recta* dominance is strongly related to disturbed sites, the habitat conditions supporting *P. recta* populations are unknown (Endress et al., 2007). Examining the relationship between *P. recta* dominance and varying habitat conditions may provide more insight into factors contributing to the establishment and spread of *P. recta* throughout the landscape. As well, identify habitat conditions that resist *P. recta* invasion.

As shown through our study, targeted goat grazing is a management option land managers may apply to control *P. recta*. However, in southeastern British Columbia, goats are not a common livestock animal. Rather, cattle are predominate because beef cattle ranching is one of the primary agricultural enterprises in the region (VAST Resource Solutions Inc., 2014). Parks et al. (2008) found early summer cattle grazing of *P. recta* lead to smaller plants with fewer flowers and subsequent seed heads. Further study will help determine whether there is a specific time and stocking rate for cattle grazing that can effectively control *P. recta* invasion within grasslands. As well, a comparison of cattle and goat grazing will determine if one grazing approach is more effective in controlling *P. recta*.

Further exploration of the belowground impacts of *P. recta* is needed to examine potential effects on grassland recovery. *Potentilla recta* alters the soil microbial community by increasing the abundance of ammonia-oxidizing bacteria (McLeod et al., 2016). These shifts in the microbial community may leave a soil legacy, which may affect the success of grassland recovery. Native *Potentilla* species, including *P. gracilis* and *P. arguta*, and the closely related

species, shrubby cinquefoil (*Dasiphora fruticosa* (L.) Rydb.), have shown non-significant or weak negative plant-soil feedbacks to soil conditioned by *P. recta* (Callaway et al., 2013). However, studies on the performance of grasses and other native forbs are needed to assess their success in reestablishing within *P. recta* conditioned soils, which will inform revegetation efforts. Examining the effects of *P. recta* conditioned soils on grass species is of particular interest. Our study and others have shown off-target effects of *P. recta* management strategies on native forbs. As such, seeding or planting grasses may be an initial first step in revegetation efforts to fill open niches to mitigate *P. recta* reinvasion or secondary invasion by other invasive plants.

The inference space to examine the efficacy of targeted goat grazing and aminopyralid application as management strategies to control *P. recta* within southeastern British Columbia was limited to our study areas. Risk of disease transfer between domestic goats and *O. canadensis*, lack of social acceptance of herbicide application, and the three 4 ha grazing areas applied in the study limited our scope of inference. Future studies should aim to incorporate a greater number of sites or incorporate grazing designs that allow for treatment replication at the study site. For example, herbicide application was successfully assessed in 6 m² plots, which suggests large areas of grassland are unnecessary to study herbicide efficacy to control *P. recta*. As well, it was determined through targeted goat grazing efforts that grazing can occur within a 1 ha or smaller area using reduced herd size, which reduces the need for larger areas to examine targeted goat grazing efficacy. Regardless, additional study sites are required not only in southeastern British Columbia, but throughout the distribution of *P. recta* in the province to better inform land managers of the efficacy of these management strategies. Selecting sites that vary climatically is of particular importance to provide further examination of the interaction between treatment, site, and seasonality.

Further study is also needed to examine the legacy effects of targeted goat grazing and aminopyralid application. *Potentilla recta* yield needs to be measured at peak standing crop of the year immediately following the implementation of targeted goat grazing treatments to more accurately measure whether *P. recta* yield is affected by targeted goat grazing, which will determine if a legacy effect is achieved (Mosley et al., 2017). As well, a long-term study will determine the number of years targeted goat grazing may need to be implemented to effectively limit *P. recta* recruitment and suppress *P. recta* growth. In regards to aminopyralid, an herbicide

legacy was observed in our study a year following its application. Aminopyralid has a soil residual effect, which can reduce re-application frequency (Dow AgroSciences LLC, n.d.). A long-term study will identify the time frame over which the soil residual is effective and the number of re-applications required to effectively suppress *P. recta* recruitment and growth. These studies are valuable as they will better inform land managers of the invested time required to successfully control *P. recta* within northern intermountain grasslands.

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APPENDIX A: NATIVE PLANT SEEDING TREATMENT

Objective

Seeding is an important tool in invasive plant management to mitigate re-invasion or secondary invasion by other invasive plants in plant communities where desirable species are rare or absent (Mangold, 2012a). At the Tobacco Plains field site, seeding with a native grassland seed mix, with and without fertilizer, was conducted within grazing and herbicide treatments with the objective of re-establishing native plants and suppressing *P. recta*.

Materials and Methods

A native grassland species mix composed of bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve), Idaho fescue (*Festuca idahoensis* ElmerElmer), rough fescue (*Festuca campestris* Rydb.), junegrass (*Koeleria macrantha* (Ledeb.) Schult.), yarrow (*Achillea millefolium* L.), brown-eyed Susan (*Gaillardia aristata* Pursh), and rosy pussytoes (*Antennaria rosea* Greene) (Table A.1), was applied on the Tobacco Plains field site with and without fertilizer (slow release, 14-14-14, N-P-K). The grass and forb species selected are common native species in grasslands within the region (MacKillop et al., 2018), and some, specifically *F. idahoensis* and *A. millefolium*, exhibit resistance to *P. recta* invasion (Maron & Marler, 2008b).

Table A.1. Native grassland species seed mix applied at the Tobacco Plains study site in early November 2019.

Scientific Name	Common Name	% of Seed Mix by Weight
<i>Pseudoroegneria spicata</i>	bluebunch wheatgrass	32
<i>Festuca idahoensis</i>	Idaho fescue	20
<i>Festuca campestris</i>	rough fescue	15
<i>Koeleria macrantha</i>	junegrass	10
<i>Achillea millefolium</i>	yarrow	9
<i>Gaillardia aristata</i>	brown-eyed Susan	7
<i>Antennaria rosea</i>	rosy pussytoes	7

Seeding and fertilizing were conducted in the fall from November 2-4, 2019. In each 6 m² plot within the grazing once, grazing twice, herbicide, grazing once + herbicide, and grazing twice + herbicide treatments, two 1 m² plots were established one meter from the bottom corners of the treatment plot. A cultivator and rake were used to prepare the 1 m² plots. Seed was manually broadcast at a rate of 1,500 PLS m⁻² within each of the two 1 m² plots and fertilizer was manually broadcast within one plot at a rate of 100 kg ha⁻¹ (10 g m⁻²). Following seeding, a

lawn roller was used to facilitate seed- and fertilizer-soil contact. In May and July 2020, percent cover was determined by ocular estimation to the nearest percent within the seeded and seeded + fertilized plots. Percent cover of the seeded species in the seeding experiment was compared to the cover determined for these same species in the 1 m² plot used in Chapter 3 (i.e. no seed).

Statistical Analysis

A mixed-effects general linear model (lmer function, lme4 package) was used to analyze the effects of seeding treatments (no seed, seed, seed + fertilizer) and a seeding treatment-by-month/year interaction on percent cover of *P. recta* and seeded species. Treatment and plot were considered random factors to focus the analysis on seeding treatments and account for repeated measures. Percent cover was square-root transformed to meet statistical assumptions. Statistical analyses were conducted in R 4.0.3 (R Core Team, 2020) with a significance level of $\alpha < 0.05$.

Results and Discussion

Potentilla recta cover did not differ between seeding treatments ($p = 0.884$) nor was there a seeding treatment-by-month/year interaction ($p = 0.268$; Table A.2). Similarly, cover of seeded species did not differ between seeding treatments ($p = 0.119$) and there was no seeding treatment-by-month/year interaction ($p = 0.146$). *Pseudoroegneria spicata* did not establish and cover of all other species within the seed mix, excluding *K. macrantha*, was less than 1% (Table A.2). However, average *K. macrantha* cover was less than 2.5% and cover was similar between the no seed, seed, and seeding + fertilizer treatments. *Koeleria macrantha* is a common species at the study site and its presence in the seed and seeding + fertilizer treatment likely represented pre-established plants and not seeded plants.

Seeding in the fall is often met with limited success within grasslands in the intermountain region (Hardegree et al., 2020). Failure has been associated with post-germination/pre-emergence mortality (James et al., 2011; Hardegree et al., 2020). James et al. (2011) suggests mortality may be driven by freezing and thawing of the seedbed, low moisture in the winter, physical crusting of soil, or pathogens attacking germinated seeds. To improve seeding survival, Hardegree et al. (2020) suggests seeding as late as possible in the fall to delay germination. As well, diversifying the germination rate within the seed mix to increase the

probability of seeds able to take advantage of favourable germination conditions during the fall, winter, and early spring.

Table A.2. Mean percent cover ± standard deviation of *Potentilla recta* and native grassland species within the seeded treatments (no seed, seed, seed + fertilizer) in May and July 2020 at the Tobacco Plains study site. Species in the seed mix (all but *P. recta*) are local native grassland species.

Month	Seeding Treatment	<i>Potentilla recta</i>	<i>Pseudoroegneria spicata</i>	<i>Festuca</i> sp.	<i>Koeleria macrantha</i>	<i>Achillea millefolium</i>	<i>Gaillardia aristata</i>	<i>Antennaria</i> sp.
May	No Seed	2.7 ± 6.3	0.1 ± 0.3	0.0 ± 0.0	1.6 ± 1.5	0.6 ± 1.6	0.2 ± 0.4	0.1 ± 0.3
	Seed	1.5 ± 3.1	0.0 ± 0.0	0.0 ± 0.2	1.2 ± 1.4	0.3 ± 0.6	0.1 ± 0.3	0.0 ± 0.2
	Seed + Fertilizer	2.5 ± 5.1	0.0 ± 0.0	0.0 ± 0.1	0.9 ± 1.0	0.2 ± 0.6	0.2 ± 0.3	0.0 ± 0.1
July	No Seed	2.0 ± 5.0	0.1 ± 0.3	0.0 ± 0.0	2.1 ± 2.9	0.2 ± 0.7	0.0 ± 0.1	0.1 ± 0.4
	Seed	2.3 ± 6.9	0.0 ± 0.0	0.0 ± 0.2	2.4 ± 3.1	0.3 ± 1.0	0.0 ± 0.1	0.1 ± 0.2
	Seed + Fertilizer	2.5 ± 6.3	0.0 ± 0.0	0.0 ± 0.0	1.4 ± 2.0	0.1 ± 0.2	0.1 ± 0.2	0.1 ± 0.2

APPENDIX B: SOIL PROPERTIES AT WYCLIFFE AND TOBACCO PLAINS

Table B.1. Soil properties, including moisture, pH, and nutrient concentrations (mean \pm standard deviation) at Wycliffe (n=24 per month) and Tobacco Plains (n=48 per month), sampled in May and July of 2019 and 2020. Outliers greater than three standard deviations were removed from each nutrient analysis. Significantly higher nutrients between sites are bolded (ANOVA on linear mixed model, $p < 0.05$, available nutrients log⁺¹ transformed).

Site	Month/ Year	Moisture (%)	pH	Available nutrients ($\mu\text{g g}^{-1}$)							
				NO_3^-	PO_4^{3-}	SO_4^{2-}	Cl^-	Ca^{2+}	K^+	Mg^{2+}	Na^+
Wycliffe	Overall Mean	22 ± 10	5.5 ± 0.5	17 ± 16	8.5 ± 3.1	7.6 ± 7.6	27 ± 15	10 ± 4.2	28 ± 17	1.7 ± 0.3	6.8 ± 3.2
	May 2019	22 ± 6.2	5.5 ± 0.4	37 ± 21	7.8 ± 2.5	6.6 ± 5.6	19 ± 8.9	11 ± 5.6	24 ± 13	1.7 ± 0.4	5.6 ± 2.7
	July 2019	23 ± 7.9	5.4 ± 0.4	8.2 ± 5.4	8.6 ± 2.9	5.6 ± 2.2	32 ± 9.0	9.8 ± 2.9	27 ± 12	1.7 ± 0.2	8.5 ± 2.4
	May 2020	32 ± 7.2	5.8 ± 0.5	12 ± 5.1	8.8 ± 2.5	3.5 ± 1.9	27 ± 20	8.9 ± 3.3	26 ± 20	1.9 ± 0.2	5.2 ± 3.4
	July 2020	8.5 ± 2.8	5.5 ± 0.6	9.0 ± 6.9	9.0 ± 4.2	15 ± 11	32 ± 17	11 ± 4.4	36 ± 21	1.4 ± 0.3	7.9 ± 2.9
Tobacco Plains	Overall Mean	17 ± 11	5.9 ± 0.7	5.3 ± 3.0	8.7 ± 4.5	5.2 ± 7.0	30 ± 22	9.2 ± 3.5	26 ± 27	1.5 ± 0.3	7.5 ± 3.9
	May 2019	14 ± 6.2	5.9 ± 0.6	5.0 ± 3.1	6.8 ± 2.3	4.8 ± 6.6	19 ± 8.3	8.6 ± 3.4	14 ± 10	1.5 ± 0.1	6.5 ± 3.5
	July 2019	10 ± 3.2	5.7 ± 0.6	5.4 ± 2.6	7.5 ± 2.2	4.4 ± 2.1	31 ± 14	8.9 ± 2.0	21 ± 15	1.4 ± 0.1	8.1 ± 2.7
	May 2020	33 ± 6.3	6.3 ± 0.6	5.1 ± 2.4	11 ± 6.5	2.3 ± 1.1	35 ± 36	8.5 ± 2.1	34 ± 43	1.9 ± 0.2	6.5 ± 4.7
	July 2020	9.7 ± 4.9	5.8 ± 0.9	5.6 ± 3.8	8.9 ± 4.1	9.9 ± 11	34 ± 16	11 ± 5.0	33 ± 22	1.5 ± 0.4	8.7 ± 4.0

Table B.2. Soil total carbon and nitrogen at Wycliffe (n=24) and Tobacco Plains (n = 48), sampled in July 2019. Significantly higher nutrients between sites are bolded (ANOVA on linear mixed model, $p < 0.05$).

Site	Total Nutrients (%)				
	TC	TIC	TOC	TN	TON
Wycliffe	6.8 ± 1.4	0.1 ± 0.0	6.7 ± 1.4	0.5 ± 0.1	0.5 ± 0.1
Tobacco Plains	3.7 ± 0.9	0.1 ± 0.0	3.6 ± 0.9	0.3 ± 0.1	0.3 ± 0.1

APPENDIX C: ABOVEGROUND BIOMASS

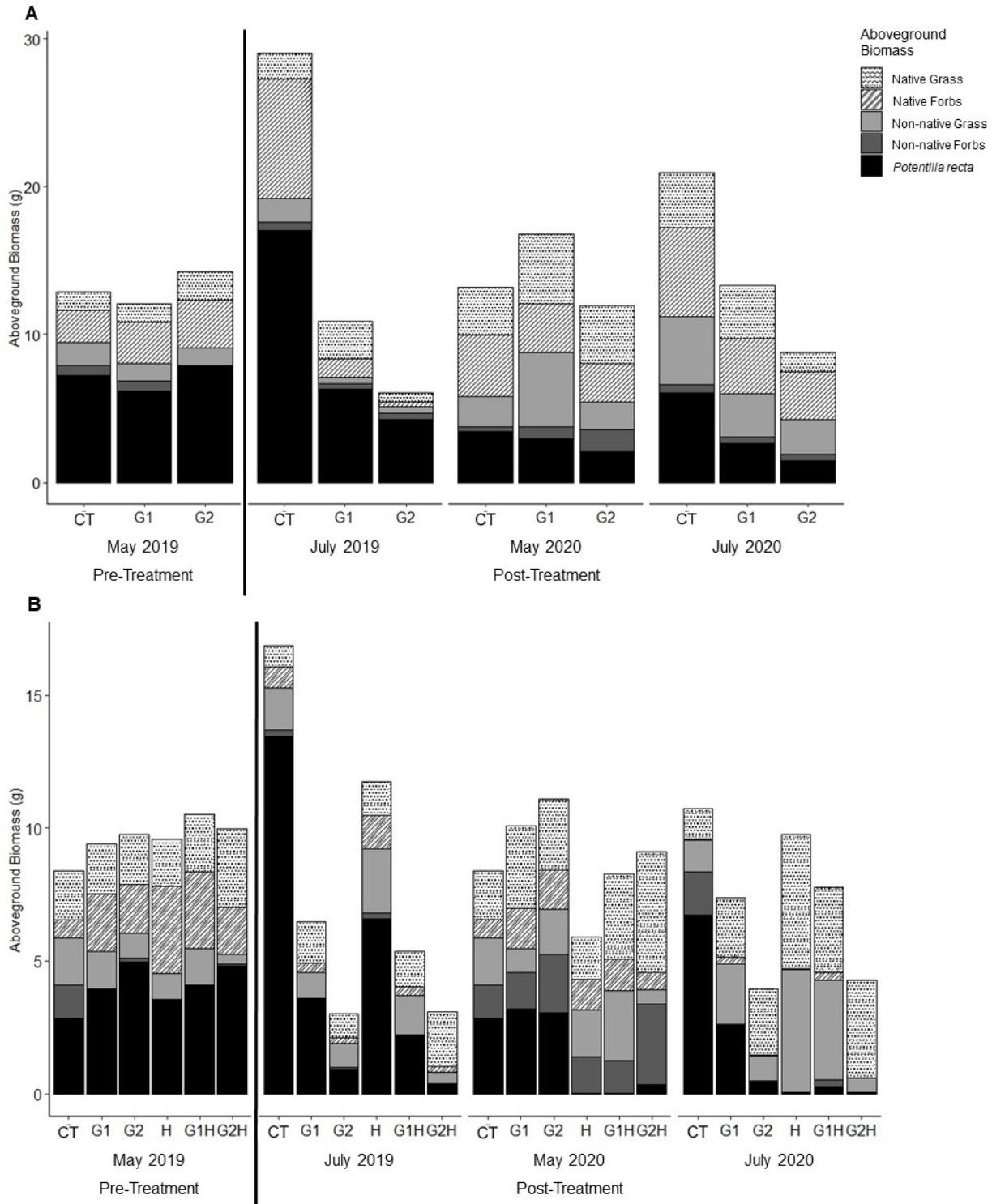


Figure C.1. Aboveground biomass of *Potentilla recta*, native and non-native forbs, and native and non-native grasses pre- and post-treatment at Wycliffe (A) and Tobacco Plains (B), separated by month/year and treatment (CT: control, G1: grazing once per year over 2 years, G2: grazing twice per year over two years, H: herbicide applied once, G1H: grazing once + herbicide, G2H: grazing twice + herbicide).

APPENDIX D: INDIGENOUS AND PUBLIC ENGAGEMENT

The invasion of *P. recta* within grasslands in the East Kootenay Region of southeastern British Columbia, Canada, is of concern to Tobacco Plains Indian Band (Yaqt ?a·knuq̣li ‘it First Nation) as well as several organizations in the region, including the East Kootenay Invasive Species Council and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development. Indigenous and public engagement was a key component of this research project to address concerns regarding *P. recta* invasion within grasslands, with focus on identifying strategies to effectively manage *P. recta*.

Research Initiation

The Lands and Resources Department of Tobacco Plains Indian Band was working with Keefer Ecological Services Ltd., who I was employed with, to manage invasive plant infestations on reserve. *Potentilla recta* was an invasive plant of concern, particularly within grasslands; however, we were uncertain of which management strategy most effectively controlled *P. recta*. The Lands and Resources Manager of Tobacco Plains Indian Band was interested in identifying management strategies to control *P. recta*, which led to the creation of this research study.

Engagement Efforts

Various engagement efforts were conducted to communicate information regarding the research study to members of Tobacco Plains Indian Band and the general public within the East Kootenay Region.

Memos

Memos were created to communicate information regarding the field study to community members of Tobacco Plains Indian Band (Fig. D.1). Memos were posted on the Tobacco Plains Indian Band Administration Facebook page and they included:

- A brief description of the study design, highlighting the management treatments that would be implemented and when treatments would be applied.
- The timeframe in which sample and data collection and targeted goat grazing would occur in Year 2 of the study.
- A brief description of the native grassland seeding treatments and when they would be applied.

Sulphur cinquefoil invasion of rangelands in East Kootenay, BC: Identifying mechanisms of invasion and best management practices

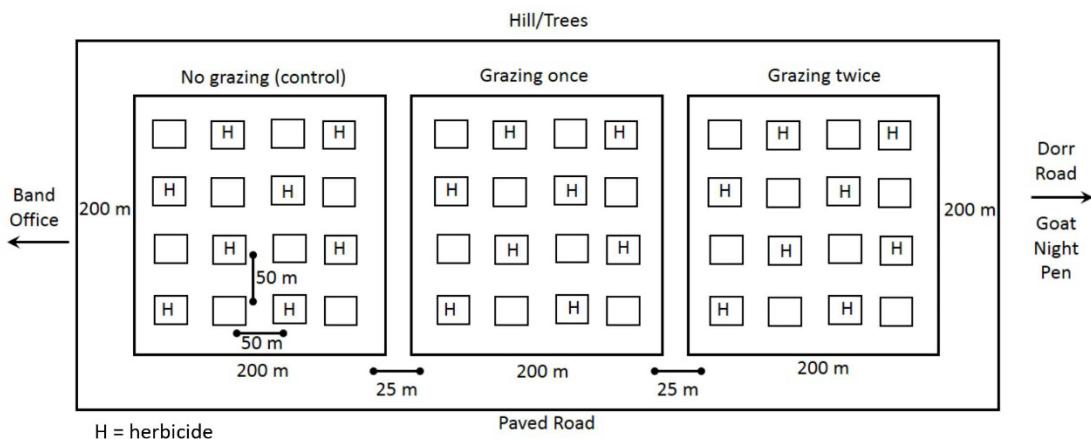
The Research Study

Sulphur cinquefoil is an invasive weed from Eurasia. It has invaded large areas of grassland and rangeland in the southern Rocky Mountains, including Tobacco Plains Indian Reserve. Tobacco Plains Indian Band is partnering with the University of Saskatchewan to begin a two-year research study in May 2019 to examine which of the following management strategies will most effectively control sulphur cinquefoil invasion on reserve rangelands.

- 1) Targeted goat grazing once in early June,
- 2) Targeted goat grazing twice per season (early June and early-July)
- 3) Targeted goat grazing once with herbicide application in mid-July,
- 4) Targeted goat grazing twice with herbicide application in mid-July, and
- 5) Herbicide application in mid-July only.

Within each of these treatments seeding of native rangeland species with and without fertilizer addition will also be examined.

The Research Design



There will be three 4 hectare (ha) study areas located on the rangeland south of the Band Office. One area will be grazed once, one area will be grazed twice, and no grazing will occur in the third area. Within each of these areas, herbicide will be applied in designated plots. The corners of each 4 ha area will be marked with a metal pole, which will remain on the rangeland during the entire study. Within each of the 4 ha areas, 6m x 6m plots will be set up and marked with rebar and wooden stakes. These markers are important to identify where sample and data collection will take place. They will be flagged with flagging tape or spray painted for visibility. All rebar and wooden stakes will also remain on the rangeland for the entire duration of the study.

If you have any questions about the study, please contact Tom Phillips, Land and Resource Manager, at 250-887-3461 Ext. 3411 or tphillips@tobaccoplains.org.



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May 14, 2019

Figure D.1. Example of a memo posted on the Tobacco Plains Indian Band Administration Facebook page regarding the field study.

Presentations

On May 9, 2019, I gave a presentation at the East Kootenay Invasive Species Council Annual General Meeting to discuss the proposed field study to examine the efficacy of goat grazing conducted once versus twice, aminopyralid application, and integrated grazing and aminopyralid application, to manage *P. recta* within degraded grasslands in the East Kootenay Region. On June 21, 2019, I presented a poster at the Tobacco Plains Aboriginal Day event that provided information on the biology of *P. recta* and a description of the field study design as well as the management treatments being examined to control *P. recta*. On November 10, 2020, I presented key findings of the field study to the Chief and Council of Tobacco Plains Indian Band. Further, on November 17, 2021, I presented key findings from the field study and the seed bank study at the East Kootenay Invasive Species Council Annual General Meeting.

Radio Interview

Dennis Walker, radio host at 2Day FM (previously Summit 107), located in Cranbrook, British Columbia, invited me to be interviewed on his radio show. The radio interview took place on June 27, 2019. I discussed the management strategies that I was examining in my field study to control *P. recta*, with particular focus on targeted goat grazing, as it is an invasive plant management strategy that individuals and organizations in the region are becoming more interested in learning about and applying.

Social Media: Facebook

Vahana Nature Rehabilitation conducted the targeted goat grazing for the field study. The company has a Facebook page and during the implementation of targeted goat grazing in both years of the field study, the owner posted videos on the Facebook page of the goats grazing *P. recta*, a description of the grazing treatments being examined, and the progress of the field study.

Community Barbeque

On July 8, 2019, I facilitated a community event at Tobacco Plains, with assistance from the Communications Liaison of Tobacco Plains Indian Band. The event included a tour of the field study to learn about the management strategies that were being examined to control *P. recta* and to demonstrate the research plots. Following the field tour a barbecue was held at the camp

where the goats were being kept, which provided the opportunity to introduce community members to the goats that were grazing *P. recta*. Four individuals attended the field tour and 32 individuals attended the barbecue.

Internship

In August 2020, I started a four-month internship in the Lands and Resources Department at Tobacco Plains Indian Band. The internship gave me the opportunity to be introduced to and get to know community members of Tobacco Plains Indian Band as well as staff in the Band office. I was also able to learn about and engage in various land management initiatives that were being undertaken by the Lands and Resources Department.