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Suppression of *Potentilla recta* by targeted goat grazing and aminopyralid on northern intermountain rangelands

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Abstract

Sulphur cinquefoil (*Potentilla recta* L.) is an invasive perennial forb threatening rangelands in western North America. To identify best management strategies to control *P. recta*, we examined targeted goat (*Capra hircus* L.) grazing conducted once (pre-flowering) versus twice (pre-flowering and flowering and seed set), aminopyralid application, and integrated targeted grazing and aminopyralid as management strategies. We also examined the interaction between treatments and seasonality (spring and summer) and explored the possibility of off-target effects to non-target species. Two intermountain rangelands 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 g ai 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 with the control, with no differences between targeted grazing treatments. In May 2020, before 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% to 99% less in the herbicide-only and targeted grazing plus herbicide treatments. In July 2020, declines in biomass and seed heads in the herbicide-only and targeted grazing plus herbicide treatments did not differ from grazing twice, and aminopyralid effects did not differ among the three herbicide treatments. Further research is required to examine legacy effects of targeted goat grazing and aminopyralid on *P. recta*, establish reapplication frequency of treatments, and determine whether integrating targeted goat grazing and aminopyralid is needed in the long term to manage *P. recta*. A long-term study is also needed to examine off-target effects from targeted goat grazing and aminopyralid and ways to mitigate these effects to promote healthy native rangeland plant communities.

Introduction

Rangelands are a key land resource within western North America, providing multiple ecosystem services, such as biodiversity, wildlife habitat, and nutrient cycling, as well as cultural value through the provision of livestock forage, food, medicinal plants, and fiber (Havstad et al. 2007). However, rangeland degradation has been prevalent throughout western North America, with invasive plants posing a primary threat to the integrity of rangelands, 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 rangeland integrity within western North America (DiTomaso 2000).

Potentilla recta is a perennial forb native to Eurasia that was introduced to North America before 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 rangelands and grasslands of the semiarid Intermountain Region of the northwestern United States and southwestern Canada, *P. recta* is considered an invader of serious concern (Endress et al. 2008; Rice 1999). *Potentilla recta* is an early colonizer of disturbed sites, including roadsides, abandoned fields, and clear-cuts, but also invades natural sites, including grasslands, shrublands, open forests, and seasonal wetlands (Naylor et al. 2005; Rice 1999). It is a long-lived forb, living more than 10 yr, and it is a prolific seed producer, producing an average of 6,000 seeds per plant, which can remain viable in the soil for 3 yr (Dwire et al. 2006; Perkins et al. 2006; Rice 1999). Its longevity, prolific seed production, and seed viability contribute to *P. recta*'s ability to perpetuate its population within rangelands (Dwire et al. 2006; Rice 1999). Management of *P. recta* requires depleting the seedbank and targeting mature plants to reduce their survivability (Lesica and Ellis 2010; Perkins et al. 2006).

Management Implications

Potentilla recta (sulphur cinquefoil) is an invader of serious concern within rangelands in the semiarid Intermountain Region of the northwestern United States and southwestern Canada. Research on the management of *P. recta* has been focused within the northwestern United States; however, *P. recta* is a prominent invader within intermountain rangelands to the north in southwestern Canada. This study began addressing this gap by examining targeted goat grazing, aminopyralid application, and their integration within rangelands in southeastern British Columbia, Canada, with targeted grazing assessed at two sites and aminopyralid application assessed at one. In the short time frame of our study, targeted goat grazing applied once during the pre-flowering stage of *P. recta* and applied twice during the pre-flowering and flowering/seed set stage both effectively suppressed *P. recta*, suggesting targeted grazing using goats may be a viable option for land managers to manage *P. recta*. We also found the application of the herbicide, aminopyralid, effectively suppressed *P. recta*, and a soil residual effect was demonstrated 1 yr following the application of aminopyralid, even though just under half the maximum application rate of aminopyralid was applied (56 g ai ha^{-1}). The effective suppression of *P. recta* by aminopyralid provides an additional herbicide option for land managers to treat this plant. In the short-term, the integration of targeted goat grazing and herbicide did not provide additional suppression of *P. recta*; however, further research is required to identify whether an integrated approach provides better long-term suppression of *P. recta* compared with a single treatment approach. Both treatment options pose the risk of altering plant community composition. Off-target effects (i.e., impacts on species other than the target invasive) may be beneficial if they promote native species assemblages. However, *P. recta* control must be weighed against undesirable off-target effects to determine whether these trade-offs align with rangeland management goals and objectives. Preliminary observations from our study identified the possibility of reduced native forb biomass in response to targeted goat grazing conducted twice within a season and the potential shift to a grass-dominant system in response to *P. recta* suppression following the application of aminopyralid. Further research is needed to examine the efficacy of targeted goat grazing and aminopyralid to control *P. recta* over a larger number of rangelands in southwestern Canada. As well, additional research over a longer time frame is needed to identify the legacy effects of each treatment and the severity of off-target effects.

Research on the management of *P. recta* has been focused within the northwestern United States, although the spread and establishment of *P. recta* is becoming of increasing concern within rangelands in southwestern Canada. To our knowledge, this study is the first to examine *P. recta* management within rangelands in 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 and Mosley 2012), targeted grazing with sheep (*Ovis aries* L.) (Mosley et al. 2017), and herbicides (Endress et al. 2008; Sheley and Denny 2006). Sheep have effectively suppressed *P. recta*, reducing yield and seed viability (Mosley et al. 2017); however, goats (*Capra hircus* L.) and cattle (*Bos taurus* L.) are other potential livestock candidates, as both are known to graze *P. recta* (Frost and Mosley 2012; Parks et al. 2008). 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* (Endress et al. 2008; Sheley and Denny 2006), with picloram identified as the most effective herbicide, achieving control at 6 yr posttreatment (Endress et al. 2012). The broadleaf herbicide aminopyralid was not included in the studies conducted by Sheley and Denny (2006) and Endress et al. (2008), which examined herbicide efficacy to control *P. recta*, as both studies were conducted before the registration of aminopyralid by the U.S. Environmental Protection Agency in 2005. Although picloram was identified as an effective herbicide to control *P. recta*, harm to native forbs is a significant risk (Sheley and Denny 2006). Aminopyralid may be an alternative to picloram, as it has reduced risk to desirable native species (Halstvedt 2012; Harrington et al. 2014).

Targeted grazing and herbicide treatment are recommended as effective strategies to manage *P. recta*; however, treatment efficacy has not been compared nor has their integration been tested. 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 et al. 1997; Masin et al. 2018; Mosley 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 may be influenced by various factors, including the availability and abundance of vegetation on site, nutritional needs, experiences, and inherited and learned behaviors (Larson et al. 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 toward 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 timing of treatment implementation. For example, precipitation has been considered a factor contributing to the variation in *P. recta* response, influencing the effectiveness of management treatments, as shown by Frost and Mosley (2012), who measured greater aboveground biomass and seed production of *P. recta* during a wetter year, leading to reduced efficacy of clipping treatments. Further, short-term fluctuations in plant community richness and composition in response to summer-induced dormancy and senescence is common within rangelands in the Intermountain Region (Rice et al. 1997; Wikeem and Wikeem 2004). Examining treatment by season interactions and changes in plant community richness and composition over the growing season 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 and Smith 2012).

The purpose of this research was to identify best management strategies to suppress *P. recta* within two intermountain rangelands in southeastern British Columbia (BC), Canada. Specifically, we examined the efficacy of using (1) goats to graze *P. recta* once, during the pre-flowering stage, versus twice, during pre-flowering and flowering/seed set; (2) the efficacy of aminopyralid as a herbicide to control *P. recta*; and (3) the effectiveness of integrated targeted goat grazing and aminopyralid application versus targeted goat grazing and aminopyralid application alone.

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The combined targeted goat grazing and aminopyralid application was hypothesized to be the most effective treatment in suppressing *P. recta*, followed by the grazing-twice treatment, and then the grazing-once treatment. To provide insight into seasonal influences on treatment efficacy, the interaction of our treatments with seasonality (spring and summer) was examined, and we hypothesized that seasonality would significantly interact with treatment. Further, we measured early responses of non-target vegetation to provide insight into possible off-target effects (i.e., increases and decreases in species cover and aboveground biomass) that may occur in response to targeted grazing and herbicide treatments.

Materials and Methods

Study Sites

A 2-yr study was conducted from 2019 to 2020 on two degraded rangelands within the East Kootenay Region, BC, Canada, in the southern Rocky Mountain Trench. One site was located in Wycliffe (49.668169°N, 115.881947°W) and the other in the northern reach of Tobacco Plains Indian Band (Yaq̓it ʔa·knuqⱡi ‘it) reserve (49.071847°N, 115.119350°W). Columbia needlegrass [*Achnatherum nelsonii* (Scribn.) Barkworth], Idaho fescue (*Festuca idahoensis* Elmer), and Kentucky bluegrass (*Poa pratensis* L.) were the dominant grass species at Wycliffe. Forbs were a mix of native (e.g., silky lupine [*Lupinus sericeus* Pursh], tall cinquefoil [*Potentilla arguta* Pursh], yarrow [*Achillea millefolium* L.]) and nonnative (e.g., *P. recta*, dandelion [*Taraxacum* spp.], yellow salsify [*Tragopogon dubius* Scop.]) species, and shrub cover was limited, with only rose (*Rosa* spp.) identified. At the Tobacco Plains study site, needle-and-thread grass [*Hesperostipa comata* (Trin. & Rupr.) Barkworth], Canada bluegrass (*Poa compressa* L.), and junegrass [*Koeleria macrantha* (Ledeb.) Schult.] were the dominant grass species, and bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve] was present but sparse. A mix of native forbs (e.g., timber milk-vetch [*Astragalus miser* Douglas ex Hook.], orange arnica [*Arnica fulgens* Pursh], peak saxifrage [*Saxifraga nidifica* Greene]) and nonnative forbs (e.g., *P. recta*, spring speedwell [*Veronica verna* L.], *T. dubius*), as well as sparse shrub cover (common snowberry [*Symphoricarpos albus* (L.) S.F. Blake]), were observed. A biological soil crust layer was present at both sites; however, cover was greater at Tobacco Plains (Tobacco Plains: 24 ± 18%; Wycliffe: 1.9 ± 2.1%).

Low-elevation rangelands within the southern Rocky Mountain Trench, in the East Kootenay Region, BC, occur in a semiarid climate (MacKillop et al. 2018). Average summer season (April to September) temperatures from 2010 to 2020 were 14 ± 5.7 and 16 ± 5.7 C at Wycliffe (Cranbrook Airport, BC, 49.610000°N, 115.780000°W) and Tobacco Plains (Eureka Ranger Station, MT, 48.897800°N, 115.064400°W), respectively, and average winter season (October to March) temperatures were −1.8 ± 7.0 and 1.2 ± 6.8 C, respectively. Average total summer precipitation from 2010 to 2020 was 188 ± 70 and 207 ± 68 mm at Wycliffe and Tobacco Plains, respectively, and average total precipitation during the winter season was 178 ± 56 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 chernozem; however, stoniness and moisture deficiency limit soil quality (BC Ministry of Agriculture and Ministry of Environment & Climate Change Strategy 2018).

Study Design

Two study designs were employed, one at Wycliffe, which included three grazing treatments (no grazing [control], grazing once, grazing twice); and one at Tobacco Plains, which included six treatments, of which three were grazing treatments (no grazing [control], grazing once, grazing twice), one was a herbicide treatment, and two were grazing plus herbicide treatments (grazing once + herbicide, grazing twice + herbicide).

Grazing treatments at each site were conducted in continuous 4-ha sections representing no grazing (control), grazing once, and grazing twice. Before grazing in May 2019, eight permanent plots, 6 m^2 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 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 densest patch of *P. recta*, and a permanent plot was established within the patch to capture treatment impacts on *P. recta*. Permanent plots were 30 to 100 m apart. Because the eight experimental units per grazing treatment were grazed simultaneously by one herd of goats, neither study (Wycliffe or 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 145 adult goats and 50 kids, at approximately 1,086 kg ha^{-1} and 0.7 animal unit month 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 to 6, 2019, and June 2 to 6, 2020; Wycliffe: June 7 to13, 2019, and June 7 to 13, 2020), and the second graze occurred during the flowering and seed set stage (Tobacco Plains: July 6 to 7, 2019, and July 6 to 7, 2020; Wycliffe: July 10 to 11, 2019, and July 8 to 10, 2020). Grazing duration in 2019 and 2020 at Wycliffe was 4.1 and 3.5 h ha^{-1}, respectively, during the first graze, and 2.1 and 2.3 h ha^{-1}, respectively, during the second graze. At Tobacco Plains, grazing duration was slightly less in both 2019 and 2020 at 3.7 and 2.9 h ha^{-1}, respectively, during the first graze, and 1.6 and 2.0 h 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, AB T2C 4S6, Canada) using a backpack sprayer at a rate of 56 g ai ha^{-1} (0.23 L ha^{-1}) on July 18, 2019, during the *P. recta* flowering and seed set stage. Wind direction was southwest at a wind speed ranging from 20 to 28 km h^{-1}, and temperature was 17 C.

Data and sample collection occurred from May 23 to 30, 2019, before treatment implementation; from July 23 to 28, 2019, following the first implementation of grazing and herbicide treatments; from May 21 to 30, 2020, before the implementation of the second year of grazing; and from July 21 to 27, 2020, after grazing was completed. Cover was determined for each species by ocular estimation to the nearest percent within a permanent 1-m^2 plot located 0.5 m from the top center in the 6-m^2 treatment plot. Voucher specimens of identified species were collected and are housed in the W.P. Fraser Herbarium at the University of Saskatchewan (Saskatoon, SK, Canada). The number of seed heads of *P. recta* was recorded in a 0.25 by 0.5 m quadrat randomly placed in the 6-m^2 treatment plot, which was followed by sampling of aboveground biomass. Biomass was collected for each of the following categories: *P. recta*, native forbs, native grasses, nonnative forbs, and nonnative grasses. Biomass samples were dried over 10 to 14 d at 40 C and subsequently weighed.

Statistical Analysis

All statistical analyses were conducted in R v. 4.0.3 (R Core Team 2020) with a significance level of $\alpha = 0.05$. Each study site represented an independent experiment and was analyzed separately. 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 and number of *P. recta* seed heads. Plot was considered a random factor to account for repeated measures. A log transformation ($Y + 1$) was performed on biomass data, and a square-root transformation was applied to the number of 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 before treatment implementation. A log transformation ($Y + 1$) was conducted on biomass data from Wycliffe to meet model assumptions. All biomass and seed head values presented in the results are raw means. Average biomass of native and nonnative forbs and grasses was determined per treatment within each month/year and the proportion of native and nonnative grass and forb cover was determined per treatment in July 2020 to preliminarily identify observations of potential off-target effects from treatments at each site. Results are presented in Supplementary Figures S1 and S2.

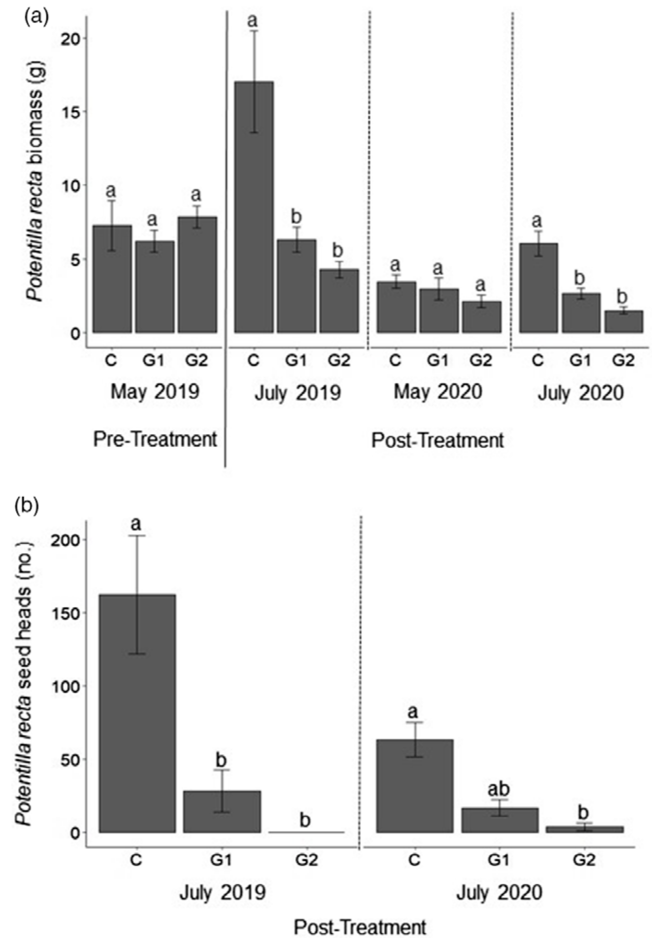

Figure 1. *Potentilla recta* aboveground biomass (A) pre- and posttreatment and number of seed heads (B) posttreatment at Wycliffe separated by month/year and treatment (C, control; G1, grazing once; G2, grazing twice). Bars represent mean with SE. Aboveground biomass and seed heads were influenced by a significant treatment by month/year interaction ($P < 0.05$; ANOVA on linear mixed models). Comparisons between treatments within a given month/year are shown with different letters indicating significant differences.

Results and Discussion

Impacts of Targeted Goat Grazing and Aminopyralid on Potentilla recta

Potentilla recta aboveground biomass and number of seed heads were reduced following targeted grazing at Wycliffe and by targeted grazing and herbicide treatments at Tobacco Plains. However, differences were not detected at all posttreatment time points (Wycliffe: biomass, treatment by month/year interaction, $P = 0.014$; seed heads, treatment by year interaction, $P = 0.047$; Tobacco Plains: biomass, treatment by month/year interaction, $P < 0.001$; seed heads, treatment by year interaction, $P < 0.001$), which supported our hypothesis that treatment and season interactions would occur.

At Wycliffe, *P. recta* aboveground biomass was lower in 2019 and 2020 following grazing once (pre-flowering) and grazing twice (pre-flowering and seed set) when compared with the control, with biomass reduced by 63% and 75%, respectively, in July 2019 and 56% and 76%, respectively, in July 2020 (Figure 1A). In May 2020, before the second year of targeted grazing, biomass did not differ between the control and targeted grazing treatments. Biomass also did not differ in May 2019, before treatments were implemented. In July 2019, the number of seed heads in both the grazing-once and grazing-twice treatments was lower than in the control, with seed heads reduced by 83% and 100%, respectively (Figure 1B). However, in July 2020, the number of seed heads was 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 with 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 (Figure 2A). Similar to Wycliffe, biomass did not differ between the control and grazing-once and grazing-twice treatments in May 2020. Biomass also did not differ in May 2019, before treatments were implemented. The number of seed heads declined by 85% and 99%, respectively, in July 2019, and 65% and 89%, respectively, in July 2020, following grazing once and grazing twice (Figure 2B). Although we measured clear decreases in the number of seed heads, we did not assess the number of seeds or viable seeds

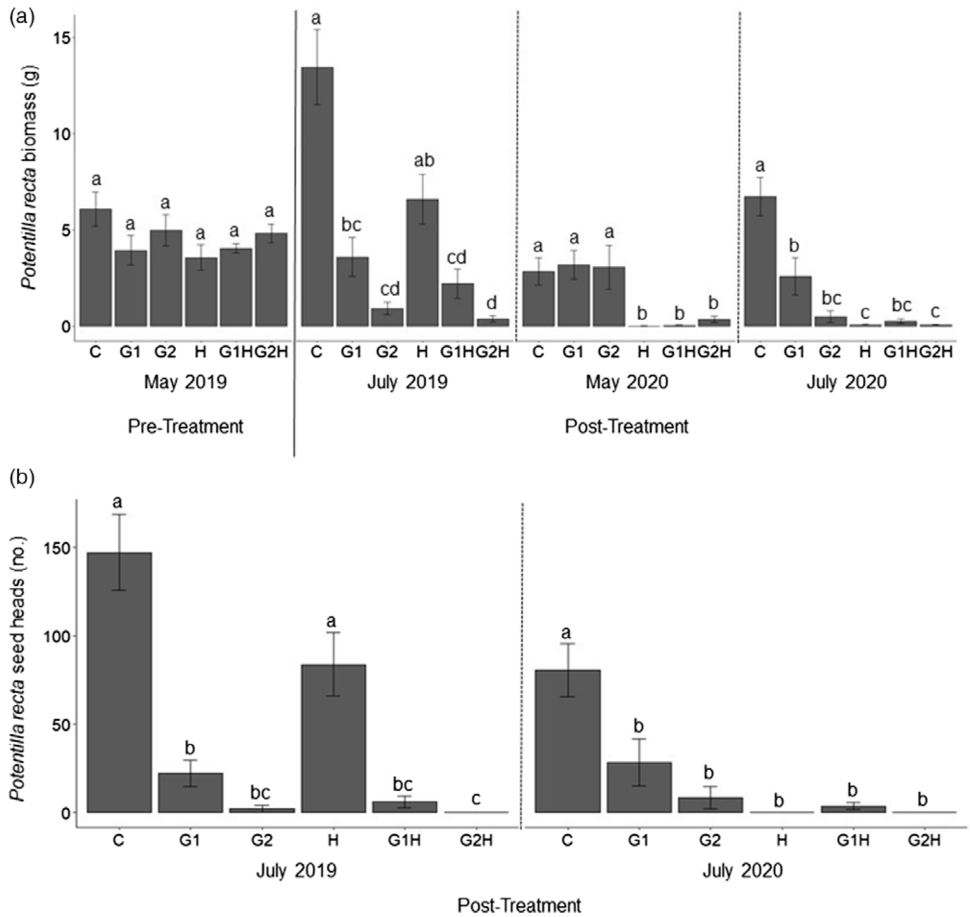

Figure 2. *Potentilla recta* aboveground biomass (A) pre- and posttreatment and number of seed heads (B) posttreatment at Tobacco Plains separated by month/year and treatment (C, control; G1, grazing once; G2, grazing twice; H, herbicide; G1H, grazing once + herbicide; G2H, grazing twice + herbicide). Bars represent mean with SE. Aboveground biomass and seed heads were influenced by a significant treatment by month/year interaction ($P < 0.05$; ANOVA on linear mixed models). Comparisons between treatments within a given month/year are shown with different letters indicating significant differences.

within seed heads, which is important for determining long-term treatment efficacy.

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 seed set 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 seed set, in both years of their study. When plants were clipped to 15 cm, the 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 2 yr, 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 (Figures 1 and 2). This is contrary to our hypothesis that significantly 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 seed set compared with two "grazing" events. Similarly, Rinella et al. (2001) found a single mowing of spotted knapweed [*Centaurea stoebe* L. ssp. *micranthos* (Gugler) Hayek] in the fall during the flowering or seed-production stage reduced *C. stoebe* 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 seed set 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 seed set effectively suppresses *P. recta* compared with two targeted grazing events and whether *P. recta* recovery following targeted goat grazing at flowering or seed set is reduced compared with 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 (Figure 2). Herbicide effects were not documented in July 2019, as aminopyralid was applied a week before data collection, which was insufficient time for *P. recta* to respond to the herbicide. *Potentilla recta* aboveground biomass was reduced by 87% to 99% in May 2020 and 96% to 99% in July 2020 in all herbicide treatments when compared with 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 with grazing once. The number of seed heads declined by 96% to 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 within rangelands compared with treatments applied alone. For example, Sheley et al. (2004) determined that the integration of a spring 2,4-D application with repeated targeted sheep grazing was highly effective in reducing *C. stoebe* density, cover, and biomass within *C. stoebe*–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 the targeted goat grazing plus herbicide treatments and the herbicide treatment alone, which was not in support of our hypothesis. Given the limited spatial and temporal scope of our study, we cannot determine whether an integrated targeted goat grazing and herbicide approach is necessary for *P. recta* control in this region. Better replicated longer-term studies are needed to fully assess the efficacy of integrated management approaches.

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 (Endress et al. 2008; Sheley and Denny 2006). 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% to 95%, 80%, and 57% at 1, 3, and 6 yr posttreatment, respectively. Our study suggests aminopyralid is an additional herbicide 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 at 1 yr following the 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 used. The decline in biomass also suggests an immediate retreatment with aminopyralid is unnecessary. A longer-term study is needed to determine whether a herbicide legacy can be achieved and to identify the reapplication frequency of aminopyralid to maintain *P. recta* control. 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 retreatment is required. However, at 1 yr following targeted sheep grazing, Mosley et al. (2017) reported 41% and 47% reduction in *P. recta* yield when measured in June and July, respectively. In our study, a decline in biomass at 1 yr following targeted goat grazing might have been measured if *P. recta* biomass was assessed later in the growing season. Although yield was reduced at 1 yr following targeted sheep grazing, Mosley et al. (2017) suggested conducting targeted grazing for at least 5 yr 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.

Off-Target Effects of Targeted Grazing and Herbicide Application

Off-target effects from targeted grazing and herbicide treatments, particularly to native forbs, is a concern land managers must consider when managing *P. recta* on rangelands. Masin et al. (2018) recorded impacts to native forbs in response to targeted sheep grazing applied to manage nonnative forbs, including *P. recta*, with 23% of the total forbs grazed representing native forbs. Although sheep preferred grazing nonnative forbs, consumption of native forbs increased as available forage of nonnative forbs decreased. The short time frame of our study and limited inference space inhibited an analysis of targeted grazing impacts to native forbs. However, we did measure a reduction in native forb biomass at Wycliffe, particularly following two grazing treatments. Biomass was reduced in July 2019 and July 2020 by 96% and 46%, respectively, in the grazing-twice treatment compared with the control (Supplementary Figure S1), which provides a preliminary observation of the possibility of off-target effects in response to targeted goat grazing. To reduce off-target effects on native forbs, Masin et al. (2018) identifies appropriate timing of targeted grazing as a critical factor.

In our study, seasonal trends in native species richness were evident at Wycliffe and Tobacco Plains, with richness higher in late May compared with late 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 midsummer 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 seed set and native forbs are completing their life cycles in response to summer drought.

Studies have reported an increase in grass cover following the application of broadleaf herbicides. Sheley and Denny (2006) measured an increase in perennial grass cover and biomass following the application of 2,4-D + clopyralid, 2,4-D amine, and picloram. As well, 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, although low richness and abundance of perennial native forbs was considered a factor that limited native forb recruitment. 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 (Ortega and Pearson 2011; Sheley and Denny 2006; Skurski et al. 2013). The short time frame of our study and limited inference space inhibited the analysis of off-target effects of aminopyralid at our Tobacco Plains field site; however, the early trends observed here may provide insight into future changes in the plant community. We measured proportionally higher native grass cover in all herbicide treatments (herbicide only: 78%; grazing once + herbicide: 70%; grazing twice + herbicide: 91%) in July 2020 compared with the control (23%) and grazing-only treatments (grazing once: 41%; grazing twice: 42%), and native grass cover exhibited a proportionally larger increase in cover compared with other functional groups

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(Supplementary Figure S2). Native grass biomass was also 344%, 182%, and 222% higher in July 2020 in the herbicide-only, grazing-once + herbicide, and grazing-twice + herbicide treatments, respectively, compared with the control (Supplementary Figure S1). As well, nonnative grass biomass was more than 100% and 65% greater in July 2020 in the herbicide-only and grazing once + herbicide treatments, respectively, compared with the other treatments (Supplementary Figure S1). Greater native and nonnative grass cover provides a preliminary observation of a possible community shift to a grass-dominated system following aminopyralid application; however, further study is required to examine this potential off-target effect.

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 for effectively suppressing nonnative dicots, such as *P. recta*, while lowering risks to native forbs (Harrington et al. 2014). Harrington et al. (2014) found that the application of aminopyralid at 30 g ai ha^{-1} reduced the abundance of nonnative 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 effectively control *P. recta* while reducing impacts to the native forb community.

Results from this study must be treated with caution, as our inference space was limited to our study areas. Furthermore, the time frame of our study was limited, only examining responses immediately following treatment and at 1 yr following treatment. Longer-term studies are needed to better understand the legacy of targeted goat grazing and aminopyralid treatments. A lack of replication of treatments, particularly treatments including herbicide application, also limits our ability to predict the effects of herbicide and targeted grazing + herbicide treatments across different sites. However, this case study adds new information on *P. recta* management in rangelands by directly comparing targeted grazing and herbicide treatment efficacy and by being the first to examine *P. recta* management within rangelands in the Intermountain Region of Canada.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/inp.2022.5

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