Experimental Control of Spotted Knapweed (*Centaurea stoebe*) within Critical Habitat of the Endangered Half-moon Hairstreak Butterfly (*Satyrium semiluna*): A Pilot Study of Blakiston Fan, Waterton Lakes National Park, Alberta

by
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B.E.S., University of Waterloo, 2015

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

in the
Ecological Restoration Program
Faculty of Environment (SFU)
and
School of Construction and the Environment (BCIT)

SIMON FRASER UNIVERSITY
BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY
Summer 2018

Approval

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Degree:	**Master of Science in Ecological Restoration**
Title:	**Experimental Control of Spotted Knapweed (*Centaurea stoebe*) within Critical Habitat of the Endangered Half-moon Hairstreak Butterfly (*Satyrium semiluna*): A Pilot Study of Blakiston Fan, Waterton Lakes National Park, Alberta**
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Date Defended/Approved:	April 18^{th}, 2018

Abstract

Spotted knapweed (*Centaurea stoebe*) is a non-native invasive forb found throughout North America that suppresses native vegetation and reduces biodiversity. The designation of Blakiston Fan (Waterton Lakes National Park, Alberta) as critical habitat for the endangered half-moon hairstreak butterfly (*Satyrium semiluna*) brought forward concerns of the effects of knapweed management practices on the hairstreak and its native larval and nectar host plants. This pilot study used a randomized complete block design to examine the within-season change in cover of spotted knapweed and silky lupine (*Lupinus sericeus*) in response to herbicide application and two timings of manual removal (i.e., mid-June and late-July). This study also examined changes in the vegetation community and relative abundance of hairstreak butterflies across the fan. Significant treatment effects (p= 0.006, $f_{3, 12}$= 6.89) were seen in the change in percent cover of spotted knapweed two weeks post-treatment between herbicide and control plots. There was no significant difference in the change in lupine percent cover among treatments (p= 0.075, $f_{3, 12}$= 2.96). Cover of native host plants and hairstreak abundance were greatest in the south fan. Increases in knapweed cover were lowest in the south fan. Based on these results, a triaged management plan was recommended with restoration efforts focused on the south fan. Recommendations for the south fan include selective herbicide application to limit spotted knapweed distribution, closure of horse trails, and a native planting and seeding experiment. Management of the north and central fan was recommended to focus on the control of knapweed monocultures through intensive herbicide application and establishing biological control agents for long-term control. Further research of the hairstreak lifecycle is needed to understand the primary mechanism of decline, as well as, research into the response of native nectar host plants to knapweed control. Monitoring the response of the vegetation community and relative abundance of hairstreaks following the Kenow fire of 2017 is key in prioritizing restoration actions for Blakiston Fan.

Keywords: species at risk; host plant; invasive species; ecological restoration; aminopyralid; vegetation mapping

Acknowledgements

Thank you to everyone who has been involved in and supported me along this journey!

First, I would like to thank Robert Sissons (Parks Canada) for providing resources and guidance throughout the field season, as well as, for his input into this report. Thank you to Parks Canada and Robert for enabling me to spend the summer working and exploring the gorgeous landscape of Waterton Lakes and the Rocky Mountains! I would also like to thank my supervisor, Dr. Doug Ransome (British Columbia Institute of Technology) for his support and direction in completing my Applied Research Project, as well as, the members of my defence committee: Dr. Ken Ashley and Dr. Anayansi Cohen-Fernández.

Thank you to all the wonderful folks without whom I would not have been able to complete the many vegetation and hairstreak surveys this summer: Kim Pearson, Jen Carpenter, Candace Jung, and many members of the Waterton Lakes Restoration Crew. Also, a huge thanks to Brett Squirrell for accompanying me on a whirlwind of a trip out to Waterton over the Thanksgiving long weekend to examine the site after the Kenow fire. Thanks to Dave Harper for providing a BCIT vehicle fully equipped for the mountain passes; and thanks to Rod Watt and Robert for coordinating site access for this visit.

Thank you to all my friends and peers whom I have had the pleasure to work alongside over the past two years. We have made it through this rollercoaster of an adventure! Looking forward to working with everyone in the future and to see what amazing things we can accomplish! Last but not least, thank you to my partner for all his support and positivity that has helped me stay on track and motivated me to push through stressful days.

March 2018
Sonya Oetterich

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A.M.F.	Arbuscular mycorrhizal fungi
COSEWIC	Council on the Status of Endangered Wildlife in Canada
E.C.C.C.	Environment and Climate Change Canada
P.N.W.	Pacific Northwest
SARA	Species at Risk Act
S.A.R.	Species at Risk
W.L.N.P.	Waterton Lakes National Park

Chapter 1. Literature Review

1.1. Introduction

Non-native invasive species rapidly colonize ecosystems and outcompete native species in the absence of natural predators and in response to disturbances (Parker and Reichard 1998, Elton 2000, Woitke and Dietz 2002, Vila and Weiner 2004). Invasion often leads to homogenized ecosystems, altered food webs, and a loss of biodiversity (Bakker and Wilson 2001, Zavaleta et al. 2001, Mac Nally and Fleishman 2004, Wagner and Van Driesche 2010). A non-native invasive species is an organism that: 1) is not native to the ecosystem it is invading; 2) can alter ecosystem function and structure; and 3) can negatively effect human health and the economy (Richardson et al. 2000). Invasive plants can alter components of ecosystem function and structure including nutrient cycling, fire regime, native biodiversity, and soil conditions (Vila and Weiner 2004).

Endangered species are particularly sensitive to invasion by non-native species. Invasive species can play a role in the decline of endangered species through limitation of resources and alteration of ecosystem structure (Severns 2008, Wagner and Van Driesche 2010, Hanula and Horn 2011). An endangered species is defined under the *Species at Risk Act* (SARA S.C. 2002, c 29) as a “species facing imminent extirpation or extinction”. The relationship between endangered insects and invasive plants is complex and varies across species. The greatest mechanism of effect of invasive plants on endangered insects is through the decrease of native plants on which the insect relies (Wagner and Van Driesche 2010). Generalist insects are often able to adapt to invasion by utilizing these exotic species (Graves and Shapiro 2003). For example, the painted lady (*Vanessa cardui*) has been observed using 42 invasive plants (Graves and Shapiro 2003). However, oviposition on invasive plants can act as a population sink (Chew 1977, Graves 1997, Graves and Shapiro 2003). Ultimately, many endangered insects are more vulnerable to loss of native host plants as they are specialists unlikely to adapt to new hosts (Graves and Shapiro 2003, Wagner and Van Driesche 2010). This vulnerability of endangered insects to plant invasion necessitates management strategies to control invasive populations.

Physical, chemical, and biological methods employed for the control of invasive plants can have variable effects on target species and may have implications on endangered species within the invaded ecosystem (Wagner and Van Driesche 2010). Conversely, endangered species are typically low in number and/or distribution making them difficult to rigorously study. Much of the literature on endangered species is anecdotal or correlation-based, rather than focused on hypothesis testing, making it challenging to understand the primary cause(s) of decline. Despite this challenge, it is imperative that ecosystem managers weight the effectiveness and potential impacts of various control methods.

The designation of Blakiston Fan (Waterton Lakes National Park, Alberta) as critical habitat for the endangered half-moon hairstreak butterfly (*Satyrium semiluna*) brought forward concerns of the effect of spotted knapweed (*Centaurea stoebe*) management on native larval and nectar host plants. To examine this challenge further, the objectives of this literature review are to: 1) provide an overview of spotted knapweed and the half-moon hairstreak (hereafter hairstreak); 2) assess the predicted response of spotted knapweed to various control methods and the potential threats to the hairstreak; and 3) assess the mechanisms of decline for the hairstreak.

1.2. Spotted Knapweed (*Centaurea stoebe*)

Spotted knapweed [*Centaurea stoebe* L. ssp. *micranthos* (Gugler) Hayek] is a widespread non-native invasive plant in grasslands and rangelands of the Pacific Northwest (P.N.W.) (Boggs and Story 1987). Spotted knapweed was first introduced to North America from Eurasia through alfalfa crops and soil from ship ballasts in the late-1800s (Watson and Renney 1974). Spotted knapweed was first recorded in North America in 1893 in Victoria, British Columbia (Groh 1944 in Watson & Renney 1974).

1.2.1. Plant Structure and Phenology

Spotted knapweed is a short-lived perennial forb of the Aster (Asteraceae) family (Watson and Renney 1974). Knapweed primarily reproduces through seed, but can reproduce vegetatively through lateral roots (Watson and Renney 1974). Additionally, an individual knapweed plant can live up to nine years (Boggs and Story 1987). Tetraploid individuals dominate the North American population (Mraz et al. 2014). Multiple rosettes emerge from a single perennial root crown in early spring (Watson and Renney 1974). Bolting begins in early May, with flowering from June to October, and seed dispersal in mid-August (Sheley et al. 1998). Seed germination occurs in early spring and fall with plants reaching reproductive-age after a single year (Watson and Renney 1974, Schirman 1981). Knapweed is characterized by deeply divided basal rosettes (Boggs and Story 1987). Stems (i.e., 30 – 100 cm tall) are upright and branch at the upper half (Watson and Renney 1974, Boggs and Story 1987). The species has alternate leaves and one-to-three flower heads per individual (Watson and Renney 1974, Boggs and Story 1987). Flowers are tubular, pink to purple with black-tipped bracts giving them a spotted look (Watson and Renney 1974).

1.2.2. Mechanisms of Invasion

Spotted knapweed suppresses native vegetation and reduces plant biodiversity through altering nitrogen cycling and soil microbial communities, increasing erosion and sediment yield, resistance to grazing, and potential release of phytotoxins (Watson and Renney 1974, Tyser and Key 1988, Lacey et al. 1989, Callaway and Ridenour 2004, Thorpe et al. 2006, Eviner et al. 2010).

Altered Biotic and Abiotic Conditions

Spotted knapweed increases its competitive advantage over native species through alteration of biotic and abiotic conditions (Watson and Renney 1974, Lacey et al. 1989, Carey et al. 2004). Associations with arbuscular mycorrhizal fungi (A.M.F.) contribute to spotted knapweed’s ability to efficiently colonize native vegetation communities (Marler et al. 1999, Carey et al. 2004). Carey et al. (2004) examined the growth of two native species and spotted knapweed both independently and together with and without A.M.F. Under all treatments, A.M.F. increased knapweed growth by 125% on average; no treatment combinations had an effect on native species growth (Carey et al. 2004). Furthermore, A.M.F. associations can indirectly increase spotted knapweed growth by parasitizing carbon from Idaho fescue (*Festuca idahoensis*); this did not affect fescue growth (Carey et al. 2004). In a similar study, Idaho fescue grew 177% larger when competing with spotted knapweed in the absence of A.M.F. compared to fescue grown with A.M.F.-associated knapweed (Marler et al. 1999). These findings suggested that A.M.F. can play an important role in increasing the invasive capacity of spotted knapweed.

An *in situ* rainfall-simulation experiment observed 56% greater runoff and 192% greater sediment yield in spotted-knapweed-dominated communities than the native bunchgrass community (Lacey et al. 1989). Knapweed typically grows in well-drained soils supported by overland flow and precipitation (Harris and Cranston 1978). This suggested that knapweed-dominated communities enhance conditions that favour knapweed.

Knapweed is relatively resistant to grazing due to its fibrous stalk and spiny flower heads (Watson and Renney 1974). This release from grazing pressure increases the plant's competitive advantage over native vegetation. Collectively, knapweed's ability to alter abiotic and biotic conditions likely plays an important role in its invasion.

Allelopathy

Callaway and Ridenour (2004) proposed the "novel weapons hypothesis", which suggests that success of an invasive plant is due to the release of novel allelochemicals to which native plants are not adapted. The same authors were the first to present evidence that suggested the release of phytotoxins by spotted knapweed (Ridenour and Callaway 2001). Lau et al. (2008) later identified overlooked experimental artifacts associated with the methods used in this founding study. Since its proposition, the role of root exude (±)-catechin in facilitating the invasion of spotted knapweed has been widely disputed (Figure #) (e.g., Bais et al. 2003, Blair et al. 2006, Weir et al. 2006, Duke et al. 2009a, 2009b, Thorpe et al. 2009). Bais et al. (2003) concluded that 100 µg/L of (-)-catechin initiates the production of reactive oxygen species in native grasses leading to plant death. However, many studies challenge these findings (Blair et al. 2005, 2006, Duke et al. 2009a, 2009b). Concentrations used by Bais et al. (2003) are three-to-five-times higher than concentrations observed in the field and effects on native vegetation are non-lethal (Blair et al. 2006). In addition, methods used for the extraction of (-)-catechin were not reproducible (Blair et al. 2006). Furthermore, a dose/response experiment comparing the effects of (-)-catechin and (+)-catechin on grasses native to Montana found the two root exudes to be weakly phytotoxic (Duke et al. 2009a). Additionally, (-)-catechin acted as a strong antioxidant, rather than initiating the production of reactive oxygen species (Duke et al. 2009a). Perry et al. (2007) conducted the largest analysis of (±)-catechin in soil of sites infested (i.e., >20% cover) with spotted knapweed to date. Authors collected 402 samples across 11 sites in Montana (9), Idaho (1), and British Columbia (1), most with a single sampling event (Perry et al. 2007). Only 20 samples from a single site during a single mid-May sampling event showed detectable levels of (±)-catechin; this was attributed to local and seasonal conditions (Perry et al. 2007). Most notably, blanks were used to detect contamination and corresponding data was omitted; however, blanks were not used in any studies reporting high soil (±)-catechin concentrations (Perry et al. 2007). Ultimately, the novel weapons hypothesis may partially explain the vigor of the invasion of spotted knapweed, but the reliability of available data is unclear. Further research is needed into the role of (±)-catechin before definitive conclusions can be made.

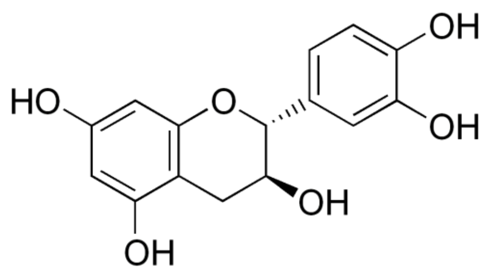

Figure 1. Molecular structure of (±)-catechin.

Seed Productivity and Viability

Knapweed has high seed productivity (5,000 to 40,000 seeds/m^2), high seed viability, and a range of conditions for seed germination – all factors which support its persistence as an invasive plants (Schirman 1981, Nolan and Upadhyaya 1988, Wallander et al. 1995). For example, up to 22% of knapweed seeds remained viable following digestion by mule deer (*Odocoileus hemionus hemionus*) and sheep (*Ovis aries*) (Wallander et al. 1995). In addition, spotted knapweed adults exhibit germination polymorphism enabling reproduction under a range of environmental conditions (Nolan and Upadhyaya 1988). This enables a single adult to produce seeds of three germination behaviours: non-dormant seeds, light-sensitive dormant seeds, and light-insensitive dormant seeds (Nolan and Upadhyaya 1988). Furthermore, knapweed seed germination is more rapid under dry conditions relative to moist conditions (Watson and Renney 1974, Davis et al. 1993). These factors increase knapweed's ability to colonize a diversity of environmental conditions across seasons when native vegetation may be dormant.

Polyploidy

Spotted knapweed's ability to readily adapt to new ecosystems and environmental stochasticity can be attributed to its polyploidy (Broz et al. 2009, Te Beest et al. 2012). Approximately 98% of spotted knapweed in North America is tetraploid, compared to the European population which is predominantly diploid (Mraz et al. 2014). Both ploidies were introduced into North America, however, the tetraploid has been far more successful at colonizing new environments (Broz et al. 2009). Tetraploidy increases a plant's ability to invade by buffering deleterious alleles and enabling adaptation to a variety of environmental conditions (Te Beest et al. 2012). Furthermore, North American knapweed tetraploids more rapidly reach reproductive age with > 75% flowering in the first year (7% death), relative to < 50% flowering (> 60% death) observed in European diploids (Broz et al. 2009). This increases knapweed's capacity to rapidly colonize an area through high seed productivity regardless of the age-class distribution of the population.

1.2.3. Impacts of Invasion

At least 15 *Centaurea* species have colonized the P.N.W.; these species and are considered one of the most significant challenges in rangeland management (DiTomaso 2000). Harris and Cranston (1978) estimated that up to 10.7 million ha of western Canada is susceptible to colonization by *Centaurea* species. Estimates of the extent of infestation by knapweed are largely variable and likely under-representative of the current extent as these estimates are out-of-date. DiTomaso (2000) estimated 2.9 million ha of western United States rangeland is infested by spotted knapweed. Alternatively, Sheley et al. (1998) estimated over 2.5 million ha of western United States and Canada have been infested by spotted knapweed. Spotted knapweed invasion is of particular concern in Montana where an estimated 1.8 million ha has been colonized (Lacey et al. 1989). Annual rangeland losses within the state as a result of knapweed infestation are estimated between $42 and $155 million (Griffith and Lacey 1991, Hirsch and Leitch 1996). The most likely mechanism by which knapweed impacts rangeland productivity is through reducing native plant productivity by 60 to 90% (Eviner et al. 2010). Knapweed is unpalatable to most ungulates, thus limits forage (DiTomaso 2000).

In addition to its large economic impact, spotted knapweed invasion has large-scale ecological implications. Knapweed invasion is correlated with a decrease in native species richness and can threaten the persistence of rare species (Tyser and Key 1988, Lesica and Shelly 1996, Thompson 1996). For example, recruitment and population growth of Sapphire rockcress (*Arabis fecunda*), a rare endemic forb, was significantly lower in areas with spotted knapweed compared to plots where knapweed was controlled (Lesica and Shelly 1996).

Changes to the vegetation community associated with knapweed invasion can have implications for the native faunal community. Loss of native vegetation has negative impacts on food availability for elk (*Cervus elaphus*) in their winter range (Spoon et al. 1983 in Sheley and Jacobs 1997). Hakim (1975) observed a 98% reduction in elk use of knapweed-infested rangeland compared to a native bluebunch wheatgrass (*Pseudoroegneria spicata*) community. Furthermore, Thompson (1996) saw a significant increase in elk use of historical range following the control of spotted knapweed, in addition to an increase in native grasses.

1.2.4. Control Methods

Due to its large-scale invasion throughout western North America, a wide range of spotted knapweed control methods have been studied including herbicide application, manual removal, biological control, mowing, burning, and grazing (e.g., Olson and Wallander 2001; Rinella et al. 2001; Emery and Gross 2005; MacDonald et al. 2013). Spotted knapweed is listed as a prohibited noxious weed under the *Alberta Weed Control Regulations* (19/2010), thus all plants are required to be rendered non-viable. The following section will explore the effectiveness of these methods in controlling spotted knapweed and their potential risk to native forbs and the hairstreak (Table 1).

Herbicide Application

Aminocyclopyrachlor (Navius®), aminopyralid (Clearview®, GF-871®, GF2050®, Milestone®, Reclaim II A®, Restore A®, Sightline®), picloram (Tordon 22K®), and 2,4-D (Restore B®, Reclaim II B®, Restore II®) are registered for use in the control of spotted knapweed in Canada (Pest Management Regulatory Agency 2017). Other chemicals used to control knapweed outside of Canada include clopyralid, dicamba, and glyphosate; however, they will not be discussed further as they are not approved for use in Canada (Sheley et al. 2001, MacDonald et al. 2013).

Table 1. Summary of literature regarding the effectiveness of control methods for spotted knapweed and relative risk to native forbs and the hairstreak.

Control Method	**Recommended Application**	**Effectiveness**	**Risk to Native Forbs**	**Risk to Half-moon Hairstreak**	**References**
Herbicide	Aminopyralid or Picloram. Spring and/or fall application.	Control sustained multiple years (i.e., 2-6) post-treatment.	Moderate*	Unknown	Kyser et al. 2013 Davis et al. 2016
Manual removal	Before seed set. Remove root crown.	Persistent pulling can control. Optimal as a follow-up to herbicide.	Low**	Low	Sheley et al. 1998 Abella 2001 Duncan et al. 2011 MacDonald et al. 2013
Biological control	*Larinus minutus* and *Cyphoclonus achates*	Reduction in seeds per seed head and decreased plant vigor, respectively. > 10 years to establish populations.	Low**	Moderate$^{\Delta}$	Jordan 1995 Wilson and Randall 2005 Story et al. 2008 Bouchier and Crowe 2011
Mowing	Conflicting recommendations for timing and frequency.	Short-lived. Conflicting results. Annual application may lengthen effect.	High†	High	Watson and Renney 1974 Rinella et al. 2001 MacDonald et al. 2013
Burning	Before seed set. High density areas of only knapweed.	Decrease biomass and additions to seed bank. Will not kill seeds in seed bank.	High	High	Sheley et al. 1998 Emergy and Gross 2005 MacDonald et al. 2007 MacDonald et al. 2013
Grazing	Before seed set. Quarantine sheep 7-10 days post grazing.	Decrease seed heads and biomass. Target younger plants.	Moderate	Moderate	Olson et al. 1997 Olson and Wallander 2001 Duncan et al. 2011

* Selective application.
** Highly selective.
Δ Potential larval predation by *L. minutus* if larvae present on seedhead.
† Best applied to areas with native perennial grass community.

All chemicals approved for application to spotted knapweed are synthetic auxin herbicides that target broadleaf plants (i.e., dicots). Synthetic auxins mimic the action of Indole-3-acetic-acid, the auxin phytohormone (Grossmann 2003). Auxin plays a key role in regulating plant growth; elevated concentrations of auxins causes plant growth to accelerated to levels that lead to lethal damage (Grossmann 2003). Plant death through application of synthetic auxins occurs in a three-step process:

1. Plant growth is stimulated increasing ethylene synthesis and abnormal growth patterns (e.g., leaf epinasty, swelling, and stem curling);
2. Root and shoot growth is inhibited, the stomata close, and starches and reactive oxygen species build-up; and
3. Membrane and vascular systems fail, leading to wilting and plant death (Grossmann 2010).

The effectiveness of herbicide application in the control of spotted knapweed varies depending on the type of chemical and the frequency of application (Sheley et al. 2004, Pfleeger et al. 2012, MacDonald et al. 2013). Aminocyclopyrachlor was registered under the *Pest Control Products Act* (S.C. 2002, c. 28) in 2014 (RD2014-30). There is little information available regarding the effects of this herbicide on spotted knapweed as it is the most recent chemical approved for its control. A single fall application of aminopyralid can maintain control of spotted knapweed two years post-treatment (Davis et al. 2016). Kyser et al. (2013) observed similar results with a low concentration winter (i.e., January to March) application of aminopyralid to a related species, yellow starthistle (*Centaurea soltstitialis*). Control effects of a single application of picloram are sustained three years post-treatment (Rice et al. 1997; Sheley et al. 2001; Pokorny et al. 2010). Furthermore, Sheley et al. (2000) saw a consistent reduction in knapweed three years post-treatment regardless of the plant life stage and timing of treatment. Long-term control of spotted knapweed can be sustained six years post-treatment from a single broadcast application of picloram (Ortega and Pearson 2011). Effects of 2,4-D in controlling spotted knapweed were short-lived when applied as a stand-alone control method (Sheley et al. 2004). Most studies of the effects of 2,4-D on spotted knapweed are short-term and show large variability in effectiveness across time and space (Sheley et al. 2004).

Manual Removal

Manual removal is a common spotted knapweed control method as it requires little technical knowledge and training and few-to-no tools, however, efficacy of this technique is not largely studied. Manual removal must target the perennial root crown from which vegetative structures emerge each growing season (Sheley et al. 1998). Repeated and careful pulling can be an effective method of controlling spotted knapweed (Sheley et al. 1998, Abella 2001, Duncan et al. 2011, MacDonald et al. 2013). However, manual removal alone can be very labour intensive and impractical in large areas with high density knapweed (Duncan et al. 2011). MacDonald et al. (2013) found that plots treated with manual removal to supplement herbicide treatment had on average 7.1% the knapweed biomass of plots that were not pulled. Alternatively, this method can be applied very selectively to avoid impacts on non-target species, and thus may be appropriate despite the lack of research.

Other Control Methods

Herbicide application and manual removal were employed in this pilot study on Blakiston Fan; however, there are many other methods used in management of spotted knapweed including: biological control, mowing, burning, and grazing. This section will provide an overview of each of these alternative methods along with an assessment of their applicability to the study site.

Biological control (i.e., biocontrol) of plants is the use of pathogens and parasites to control invasive species (Müller-Schärer and Schroeder 1993). Flies, moths, and beetles (totaling 13 species) have been used as biocontrol agents for spotted knapweed in North America, (Wilson and Randall 2005). These insects are classified as seed-head feeders or root borers depending on their feeding behavior (Section 4.3. for species-specific information). Introduction of biocontrol agents is not considered an appropriate action for immediate management of spotted knapweed as populations typically take five years to establish (Story et al. 2006). Once established, biocontrol agents are an effective tool for long-term management of spotted knapweed (Wilson and Randall 2005; Story et al. 2008; Van Hezewijk and Bourchier 2011).

Contrary to biocontrol, mowing may be useful in the short-term management of spotted knapweed when implemented at the appropriate time and under suitable site conditions. There has been little investigation into the efficacy of mowing in controlling spotted knapweed, relative to other spotted knapweed control methods. Rinella et al. (2001) conducted a three-year mowing study of 15 timing and frequency combinations. The season of treatment had a greater effect on success than treatment frequency, and an additive effect was not seen from repeated annual mowing (Rinella et al. 2001). This is likely due to the influence of variable environmental conditions (Kennett et al. 1992). Mowing during the flowering stage reduces knapweed stem density by 85% (Rinella et al. 2001). Similarly, Watson and Renney (1974) concluded that a single mowing at the bud stage can reduce adult stem density by more than 75%, but is most effective when repeated throughout the growing season to target multiple emergence times. In contrast, relative to an integrated weed management strategy, mowing during the late-bud and early-flowering stages has low effectiveness (MacDonald et al. 2013). Mowing is most appropriate at sites with low native forb cover and as a component of an integrated weed management strategy.

Similar to mowing, controlled burns are most effective under a specific range of conditions. The effectiveness of controlled burns on spotted knapweed is highly variable and based on site conditions, timing of burns, and fire intensity (Emery and Gross 2005, Macdonald et al. 2007, MacDonald et al. 2013). Low intensity fires often stimulate seed germination and do not reach temperatures necessary to kill seeds in the seed bank (MacDonald et al. 2013). A low intensity burn as a standalone control method for knapweed can provide a disturbance that favours further knapweed invasion (Sheley et al. 1998). In contrast, Macdonald et al. (2007) found that a mid-spring burn consistently decreased knapweed biomass over three years; however, seedling density was only decreased in the first two years of treatment. Repeated burns lead to a shift in age structure of knapweed populations, reducing the number of adults contributing to the seed bank (Emery and Gross 2005). However, fire is unable to significantly reduce the abundance of adult plants regardless of burn frequency and timing (Emery and Gross 2005). Controlled burns applied to areas of high knapweed density allow for effective fire transmission, but should be limited to application in areas with few native plants (Emery and Gross 2005).

Although the effectiveness of grazing in controlling spotted knapweed is poorly studied, this technique may be useful in suppressing the competitive abilities of knapweed, thereby enabling increased success of native vegetation (Olson and Wallander 2001). Olson and Wallander (2001) examined sheep grazing in an Idaho fescue grassland infested by spotted knapweed over three years. Sheep selectively grazed knapweed leaves and flower heads and avoided the fibrous stems, but grazed the entire structure of the native grass (Olson and Wallander 2001). Furthermore, sheep grazed over 80% of knapweed individuals, but this had a less than proportional impact on cover (Olson and Wallander 2001). Alternatively, grazing was effective in shifting the age-class distribution of knapweed because sheep are most likely to graze younger, more palatable plants (Olson et al. 1997). Despite a decrease in the proportion of knapweed seeds in soil in grazed sites, Olson and Wallander (1997) observed a 35% increase in non-native Kentucky bluegrass (*Poa pratensis*) in response to three years of sheep grazing. Although grazing did not directly impact native vegetation, an increase in bare soil and colonization by Kentucky bluegrass may alter the succession of the vegetation community (Olson et al. 1997). Grazing is not an appropriate management strategy in areas with wild ungulates due to concerns of disease transmission between domestic and wild animals (Robert Sissons, Pers. Comm.).

1.3. Half-moon Hairstreak (*Satyrium semiluna*)

The half-moon hairstreak (*Satyrium semiluna*) is listed as an endangered species under Schedule 1 of the *Species at Risk Act* (SARA S.C. 2002, c 29). This species is a small (2.0 – 3.4 cm wingspan) butterfly of the Lycaenidae family with a brown-black dorsal wing colouration (Figure 2) (B.C. Southern Interior Invertebrates Recovery Team 2011). The hairstreak produces one generation each year (i.e., univoltine) with an on-wing lifespan of six to fourteen days (B.C. Southern Interior Invertebrates Recovery Team 2011). The flight period of the Alberta population is late-June to late-July; this corresponds with the flowering period of nectar host plants (B.C. Southern Interior Invertebrates Recovery Team 2011). The average seasonal dispersal of an adult hairstreak is 100 m with a maximum dispersal of 1200 m (COSEWIC 2006).

The hairstreak is at the northern extent of its range in western Canada with populations as far south as central California and east to Wyoming; American populations are considered to be stable (COSEWIC 2006). The Alberta population is distinct from populations in B.C. and the United States (COSEWIC 2006). The Waterton population of hairstreaks may be an endemic species, however, this is pending genetic analysis (Robert Sissons, pers. comm.). Furthermore, the Alberta population provides a unique opportunity for conservation as it is located on federally-owned land, whereas, the B.C. populations are primarily on private land (COSEWIC 2006).

The Waterton Lakes National Park (W.L.N.P.) population of hairstreaks is one of eight populations in Canada; the other populations are located in B.C. (E.C.C.C. 2016). More specifically, Blakiston Fan in W.L.N.P. is mapped as critical habitat for this species at risk due to the presence of larval and nectar host plants and repeated hairstreak observations (ECCC 2016).

Figure 2. Dorsal (left) and ventral (right) wing surfaces of the male (top) and female (bottom) half-moon hairstreak (*Satyrium semiluna*) specimens from Blakiston fan, Alberta. Photo Credit: N. Kondla.

1.3.1. Larval and Nectar Host Plants

The hairstreak relies on larval host plants for food and shelter for overwintering larvae, and nectar host plants as the primary food source for adult butterflies (E.C.C.C. 2016). Larval host plants include silky lupine (*Lupinus sericeus*) and silvery lupine (*L. argenteus*); nectar host plants include sulphur-flower buckwheat (*Eriogonum umbellatum*), yellow buckwheat (*E. flavum*), and Missouri goldenrod (*Solidago missouriensis*) (E.C.C.C. 2016). Structural elements such as other plants (e.g., *Artemisia* spp, *Aster* spp, *Astralagus* spp, *Elaegnus commutate*, *Potentilla* spp), rocks, and bare ground are important for mating and shelter from predators (E.C.C.C. 2016).

Silky lupine and silvery lupine are native tap-rooted perennial forbs of the pea family (Fabaceae) (Lesica 2002). Stems emerge in May, flowering late-May to July with seed set in August (St. John and Tilley 2012). It can take three to five years for a plant to produce flowers (St. John and Tilley 2012). Both silky and silvery lupines are found throughout the P.N.W. and as far south as New Mexico; the latter reaches further east to Saskatchewan and south to Texas (St. John and Tilley 2012). Both species prefer coarse textured, well-drained soils in full sun (St. John and Tilley 2012).

Sulphur-flower buckwheat and yellow buckwheat are native tap-rooted perennial forbs of the buckwheat family (Polygonaceae) (Lesica 2002). These buckwheats are found throughout the P.N.W. with the former reaching south to New Mexico, and the latter with a northern eastern range reaching to Alaska, Manitoba, and the Dakotas (Young-Mathews 2012).

Missouri goldenrod is a short-lived perennial forb in the Aster family (Lesica 2002). Flowers bloom late-July to October (Pavek 2011). Missouri goldenrod grows optimally in sandy loam to clay loam soils in full sun, but can grow in gravelly soils and partial shade (Pavek 2011). This plant is found from British Columbia to Ontario and in most mid-western and western states (Pavek 2011).

1.3.2. Mechanisms of Decline of the Half-moon Hairstreak

Similar to many species at risk, the half-moon hairstreak is poorly studied; thus, there is little understanding of the root cause of the population decline. There are three primary mechanisms of population decline: food limitation, predation, and physiological limitation (Figure 3). This section will explore the most likely mechanism in the population decline of the hairstreak.

Food Limitation

Food limitation is the most likely mechanism for the decline of the hairstreak. Although there is a lack of research on the hairstreak, there is ample evidence of the influence of food limitation on the fitness of other Lepidopterans (e.g., Boggs and Ross 1993; Schultz and Dlugosch 1999; Bauerfeind and Fischer 2005). Schultz and Dlugosch (1999) identified a positive correlation between nectar availability and life span when examining resource limitation in the at-risk Fender's blue butterfly (*Plebejus icarioides fender*); life span was similarly correlated with oviposition. Furthermore, availability of nectar host plants had a greater impact on life span than larval host plants (Schultz and

Dlugosch 1999). Similarly, Janz et al. (2005) observed that during oviposition-plant-selection, nectar availability was more important than nutritional quality of plants as a larval host. In addition, under food-limiting conditions energy resources are allocated away from reproduction to support adult survival (Boggs and Ross 1993, Bauerfeind and Fischer 2005). This suggests low availability of nectar host plants may limit population growth rates of the hairstreak.

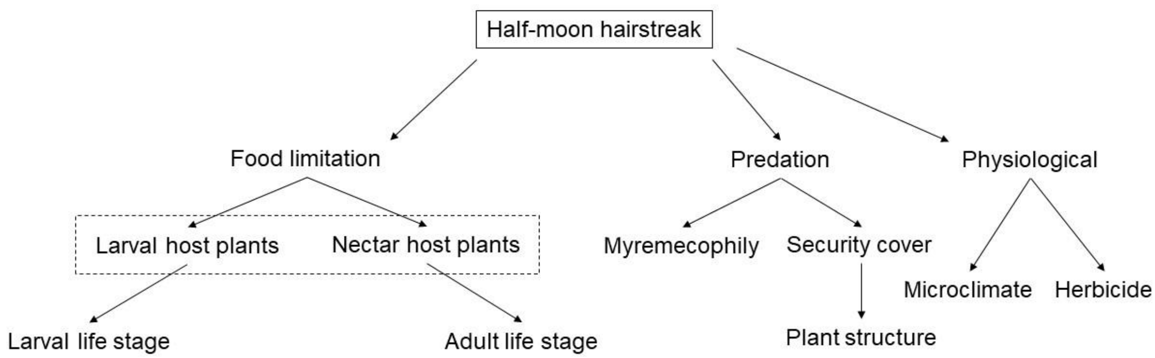

Figure 3. Mechanisms of decline of the endangered half-moon hairstreak butterfly (*Satyrium semiluna*) on Blakiston Fan, Waterton Lakes National Park, Alberta.

In addition, Schultz and Dlugosch (1999) urge that total nectar availability on site should be examined at a finer scale when managing species at risk. An increase in nectar plants does not directly increase nectar due to variability in production per plant (Schultz and Dlugosch 1999). This highlights the need for quality over quantity of native nectar host plants.

The life stage in which food-limiting conditions occur largely influences the repercussions for the individual (Bauerfeind and Fischer 2005). Food limitation during the larval stage results in a decreased body size, indirectly lowering reproductive rate (Bauerfeind and Fischer 2005). Conversely, food limitation during the adult phase will directly decrease reproduction due to reallocation of energy resources (Bauerfeind and Fischer 2005). Constraints on the population of hairstreaks may be a result of limited food availability during both larval and adult stages.

Predation

Predation is unlikely the primary driver in the decline of the hairstreak. As is common in the Lycaenidae family, there may be mutualistic relationship between ants and the hairstreak (Atsatt 1981; Pierce & Young 1986; COSEWIC 2006; ECCC 2016). This relationship is most commonly facultative mutualism; obligate mutualistic, commensal, and parasitic relationships are also present in the family (Pierce and Young 1986). The protection hypothesis proposes that ants protect larvae from predation and parasitism, and in return the larvae secrete amino acids that are consumed by ant attendants (Atsatt 1981). Although this relationship does not protect the adult life stage, and thus does not largely influence adult survival, it can increase the realized fecundity of adults in a population (Pierce and Young 1986). The co-evolution of this relationship can be evidenced by a thick larval cuticle, release of pheromones, presence of a nectar gland, and in some cases, preferential selection of oviposition sites where ants are present (Atsatt 1981). Although there are many species that have co-evolved with ant attendants, this behaviour has not been observed in Canadian hairstreak populations (E.C.C.C. 2016). However, myremecophily (i.e., mutualism with ants) has been observed in seven other species of the *Satyrium* genus, including the closely related sooty hairstreak (*S. fuliginosum*) (Ballmer & Pratt 1991). This literature suggests that there may be an existing relationship that limits predation during the larval stage. Regardless, without direct observations there is no proof that this facultative relationship may be buffering predation impacts on the population. Further investigation is needed to determine the relationship between ants and hairstreak larvae.

Female selection of oviposition sites may be an important factor in predator evasion during the flightless life stages. Wiklund and Friberg (2008) tracked oviposition behaviour and larval survival across two habitat types: meadow and rocky shore. Females preferentially laid eggs in rocky shore habitat where larval survival was highest due to decreased predation of eggs (Wiklund and Friberg 2008). This suggests that densely vegetated areas, such as knapweed monocultures, may increase the number of predators at the early life stages. Furthermore, Berger et al. (2012) observed that host plants selected for oviposition grew more vigorously and persisted longer than rejected host plants. This selection behaviour may be in pursuit of greater nutrition for larvae (i.e., food limitation) or greater security cover (i.e., predator evasion) (Berger et al. 2012). There is no evidence that the population is limited by predation during the adult phase. Larval predation may be a factor in the decline of the hairstreak, but is not likely the primary mechanism.

Physiological

There is little evidence to support the hypothesis that physiological changes resulting in microclimatic variations is the primary mechanism of decline of the hairstreak. Although temperature is the greatest predictor of butterfly species richness in Canada, the mechanism of influence is unknown (White and Kerr 2007). The influence of temperature is likely indirect because temperature is correlated with plant diversity across the country (White and Kerr 2007). Temperature may have an indirect influence on reproductive capacity through thermal threshold to flight; however, this is not a direct response of physiological processes (Berger et al. 2012).

Herbicide application may have an indirect effect on butterfly survival, but there is little evidence of deleterious physiological changes as a result of herbicide application. For example, there is a correlation between loss of nectar host plants as a result of herbicide application and a decrease in monarch butterfly observations in agricultural fields of the American mid-west (Pleasants and Oberhauser 2013). Alternatively, LaBar (2009) saw no significant changes in larval survival of the Puget blue (*Icaricia icarioides blackmorei*) in herbicide treated plots relative to control plots; however, butterflies spent significantly more time in control plots.

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Chapter 2. Blakiston Fan Site Conditions

To appropriately estimate the restoration needs of a site, it is important to understand the historical context, recent changes, ongoing stressors, and the desired future conditions. The following chapter aims to outline: 1) the history of Blakiston Fan relevant to the control of knapweed and persistence of the hairstreak population; 2) recent changes in the vegetation community and hairstreak population; 3) natural and anthropogenic stressors; and 4) desired future conditions.

2.1. Historical Conditions

Waterton Lakes National Park (W.L.N.P.) is located in the subalpine subregion of the Rocky Mountain natural region of Alberta (Natural Resources Committee 2006). The park is bordered by British Columbia to the west and Montana to the south and lies on the traditional land of the Blackfoot Nation (Siksikaitsitapi) (Figure 4) (Dempsey 2010). The park has a diverse history of land use including forestry, oil extraction, cattle grazing, crop farming, and residential and road developments (Getty 1971). The area of Blakiston Fan north of Blakiston Creek was used for grazing and farming activities until as late as the 1960s (Parks Canada n.d. b).

Blakiston Fan is located in the central area of W.L.N.P. delineated by Highway 5 to north and Middle Waterton Lake to the south. Blakiston Fan is an alluvial fan formed from the deposition of sediments during the annual flooding and receding of Blakiston Creek (Bull 1977). The creek carries sediments eroded from upper parts of the watershed to the fan. As water velocity decreases at lower elevations sediments are deposited across the landscape (Bull 1977). Coarse sediments dominate the terrain with little topsoil, high porosity, and low soil moisture content (Bull 1977). Flood events continue to alter the course of Blakiston Creek and deposit new sediments. In 1964, there was a large flood due to a heavy June rain-on-snow event that rapidly melted the large snowpack (Parks Canada n.d. a). Blakiston Creek flooded a large area of Blakiston Fan again in 1975 as a result of similar conditions (Parks Canada n.d. a).

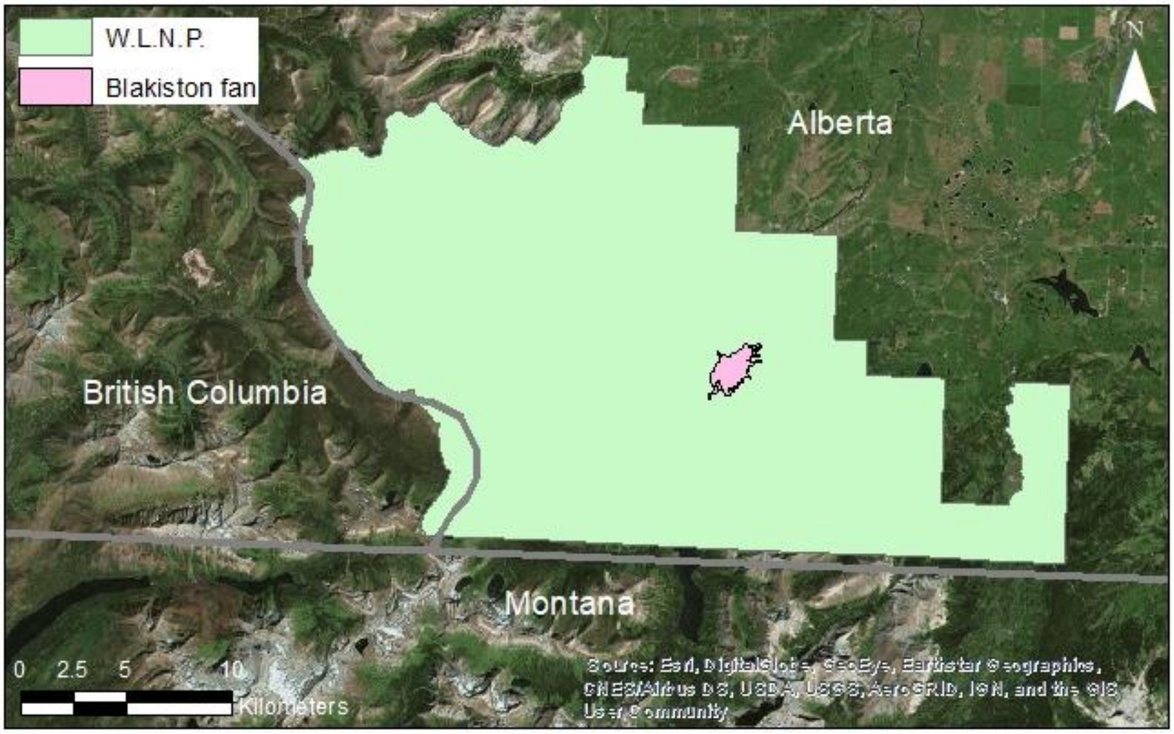


Figure 4. Waterton Lakes National Park (green) is located in southeastern Alberta, Canada. Blakiston fan (pink) is located in a central area of the park along the entrance road.

Spotted knapweed was first observed in W.L.N.P. along a roadside in 1968 (Kuchar 1973). A knapweed control program was implemented in 1979 following two years of experimental spraying (Parks Canada n.d. a). Biological control agents were first released in the park in 1994, but were not introduced onto Blakiston fan until 2012 (Table 2).

Table 2. Historical releases of knapweed biological control agents in Waterton Lakes National Park, Alberta. All release sites have unique coordinates.

Date of Release[a]	**Release Location**	**Biological Control Agent**
Summer 1994[b]	Belly River	*Urophora affinis*
31-Jul-12 and 9-Aug-12	Central Blakiston fan (1 site)	*Cyphocleonus achates*
31-Jul-12	Central Blakiston fan (2 sites)	*Larinus* spp.*
19-Aug-15	Central Blakiston fan (1 site)	*Cyphocleonus achates*
19-Aug-15	Central Blakiston fan (3 sites)	*Larinus* spp.*

a Information gathered from Parks Canada (2016), except Belly River (see b).
b Parks Canada n.d. a
* *Larinus minutus* and *Larinus obtusus* not distinguished.

In 2008, Tannas and Tannas (2009) conducted a survey of the distribution of native forbs and invasive species across Blakiston Fan (methods in Appendix A). This survey was repeated in 2013. Mapping analysis indicates change in knapweed cover across the fan over five years (Appendix C). Increases in knapweed cover of 15% and greater were prominent in the northeastern portion of the fan. Spotted knapweed cover was lowest in the southwestern corner of the fan with knapweed absent in many polygons in both survey years. The greatest decreases in knapweed cover were seen where Blakiston Creek enters the fan (north-central).

Insect populations are prone to inter-annual fluctuations in response to environmental stochasticity thus continuous monitoring in populations is important to track long-term changes (Wallner 1987). Relative abundance surveys of hairstreaks on Blakiston Fan began in the early 2000s (Table 3). Survey effort varied across years and three primary methods were used: flower-perching surveys, transects (i.e., Pollard walks), and wandering counts. This variability must be considered when examining trends in the relative abundance of hairstreaks on Blakiston Fan over this historic survey period.

Table 3. Half-moon hairstreak butterfly (*Satyrium semiluna*) observations on Blakiston Fan (Waterton Lakes National Park, Alberta) from 2003 to 2014.

Year	Survey Type	Total Transect Distance	Adult Hairstreak Observations	Researcher(s)
2003	Flower-perching survey	Unknown	3000*	N. Kondla
2004	Transects and wandering counts	1500 m	230	N. Kondla
2008	Irregular transects	1100 m	109	D. Poll and G. Poll
2009	Transects	8250 m	238	N. Kondla
2012	Wandering counts	Unknown	5**	N. Kondla
2014	Transects and wandering counts	2250 m	260	N. Kondla

* Conservative estimate
** Surveying for one hour on a single day. Few sightings likely due to adult mortality from spring frost (Kondla and Smith 2009).

2.2. Current Conditions

The main channel of Blakiston Creek shifted south during the summer of 2013. This shift made newly abandoned channels with mixed sediment and no topsoil open for colonization by vegetation. A survey of the distribution of vegetation across Blakiston Fan was repeated in 2017 in accordance with the methods described by Tannas (2013) (Appendix A). A mapping analysis revealed the changes in knapweed cover across the fan from 2013 to 2017 (Figure 5). The greatest and most frequent increases in knapweed cover were in the central part of the fan (i.e., west of Blakiston Creek and north of Marquis Hole Rd.). The area south of Marquis Hole Rd. saw little change in the cover of knapweed. Knapweed was present in all polygons surveyed in 2017.

The cover of native larval and nectar host plants varies across the fan (Figure 6). The predominant larval host plant, silky lupine, is most abundant south of Blakiston Creek with areas of 10 to 40 percent cover south of Marquis Hole Rd. and in the western portion of the fan. Yellow buckwheat, the predominant nectar host plant, is most abundant in similar areas; however, due to differences in plant structure and size, buckwheat cover is at-most five percent.

Butterfly surveys were conducted across Blakiston Fan from July 26th to August 3rd, 2017 to estimate the relative abundance of hairstreaks; probing surveys were conducted July 21st and 24th, 2017. Twenty-three individuals were identified across 54 transects (5 observations) and five flower head meandering surveys (18 observations) (Figure 7); detailed surveys methods are described in Appendix B. Other butterfly species observed on Blakiston Fan during the survey period include: Melissa blue (*Plebejus melissa*), Boisduval's blue (*Plebejus icarioides*), painted lady (*Vanessa cardui*), western white (*Pontia occidentalis*), and dark woodnymph (*Cercyonis oetus*).

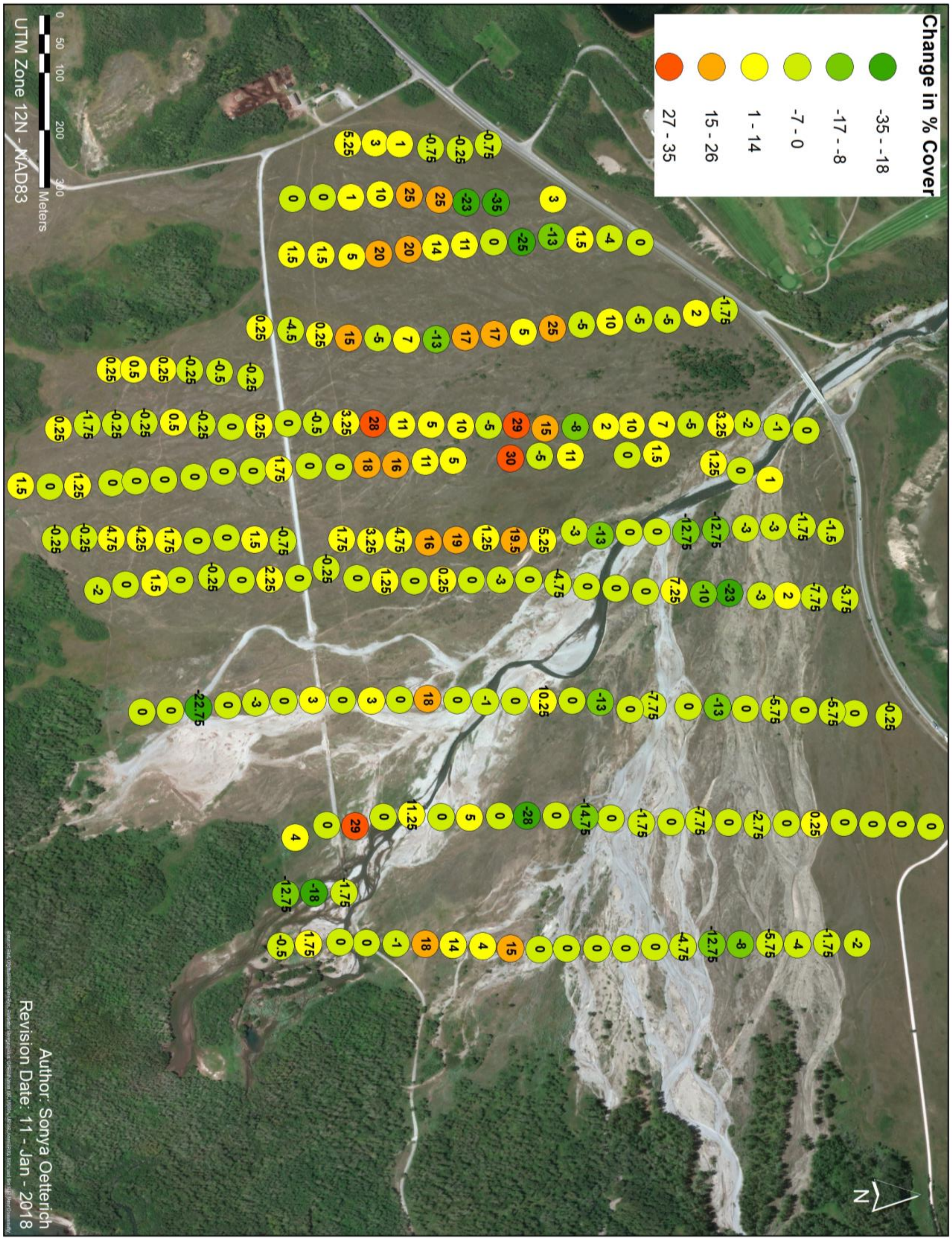
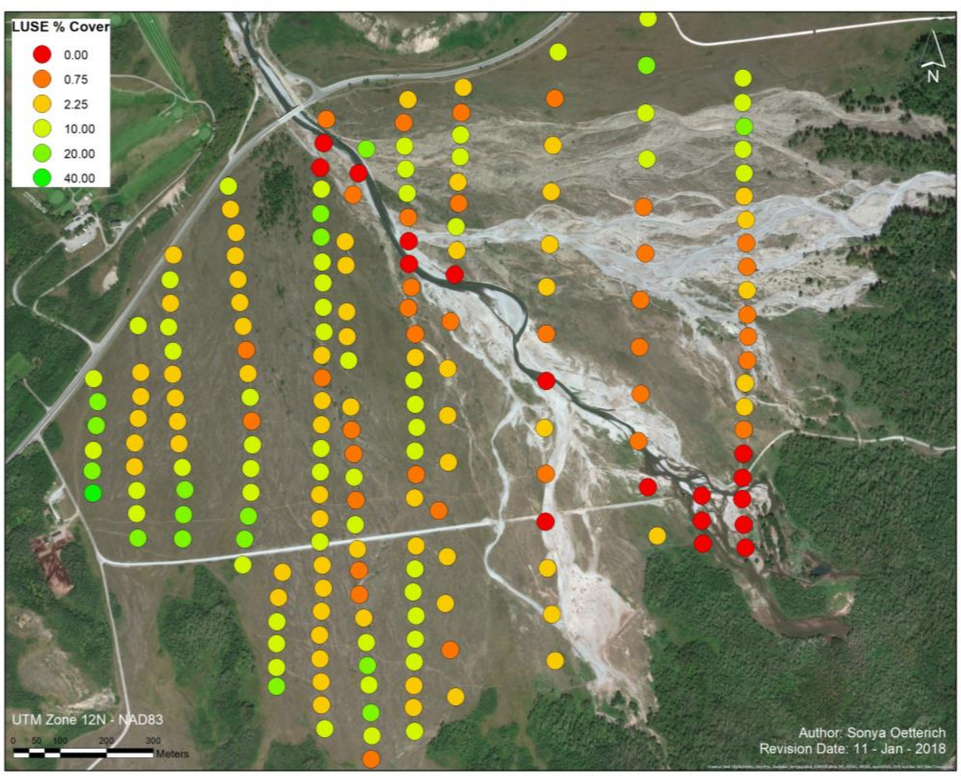


Figure 5. Change in average percent cover of spotted knapweed on Blakiston Fan, Waterton Lakes National Park, Alberta from 2013 to 2017.



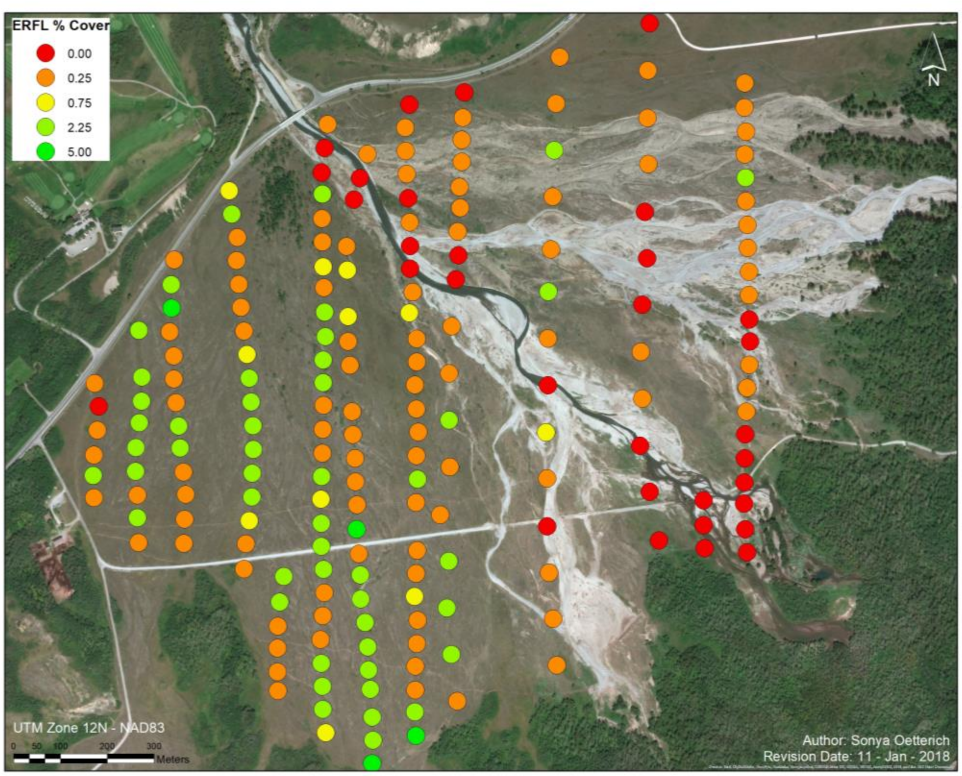


Figure 6. Average percent cover of silky lupine (top) and yellow buckwheat (bottom) on Blakiston Fan, Waterton Lakes National Park, Alberta in 2017.

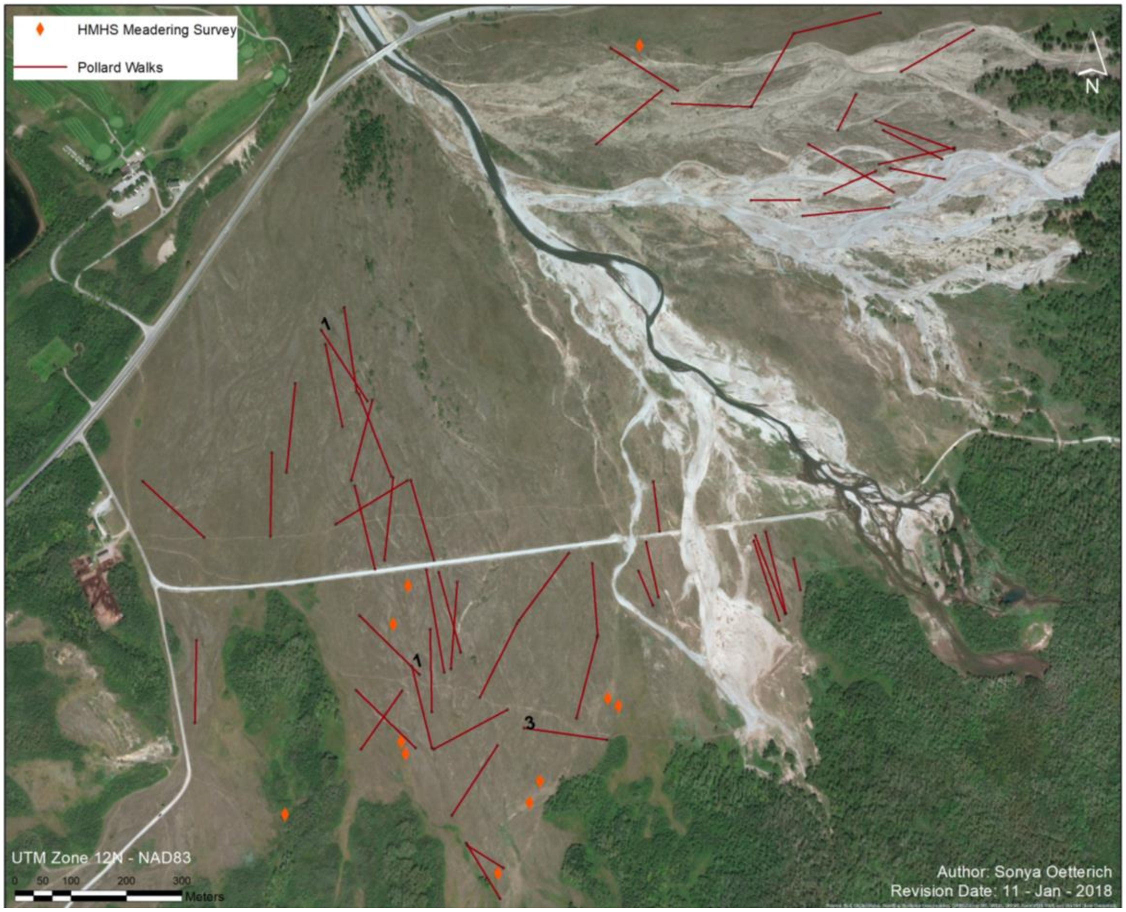


Figure 7. Summer 2017 half-moon hairstreak butterfly (*Satyrium semiluna*) observations on Blakiston Fan, Waterton Lakes National Park, Alberta. Red lines indicate Pollard walks; numbers indicate hairstreak observations along a transect. Orange diamonds indicate location of hairstreak observations during meandering surveys. The location of seven observations made during meandering surveys was not recorded.

The Kenow fire entered W.L.N.P. on September 4th, 2017 and reached Blakiston Fan by September 12th, 2017. An evacuation order was issued for the park on September 8th, 2017 and remained in place until September 20th, 2017. The fire covered approximately 38,100 ha. The Kenow fire burned the central and southern portions of the fan with little area burned between Haybarn Rd. and Blakiston Creek.

A post-fire site visit was conducted to assess the characteristics of the burn across Blakiston Fan on October 6th, 2017. The burn on the north fan extended from Hay Barn Rd. southwest towards Blakiston Creek. The upper bank of an abandoned channel east of the creek delineated the edge of the burn (Figure 8a). Large areas of the south fan remain unburned. Areas with dense graminoids were fully charred (Figure 8b); this was common on the central fan. Knapweed stems remained standing across burned areas, but foliage was removed (Figure 8c). Overall, the burn was discontinuous leaving patches of native and invasive vegetation (Figure 8d).

Figure 8. Post-fire conditions on Blakiston Fan, Waterton Lakes National Park, Alberta. a) Edge of burn on the north fan. b) Charred soil and vegetation in an area of formerly dense graminoids on the central fan. c) Knapweed stalks remain upright after burn. d) Unburned nectar host plant (*Eriogonum falvum*) on the south fan.

2.3. Ecological Stressors

2.3.1. Invasive Species

Relatively dry, hot, unforested sites in close proximity to roadways, similar to Blakiston Fan, are particularly vulnerable to invasive species relative to cool, moist forests (Menuz and Kettenring 2013). Invasive plants continue to be a challenge on Blakiston Fan. Six invasive plants were identified across the fan during summer of 2017 (Table 4). Knapweed species are the highest priority of concern due to their abundance throughout the park and their ability to rapidly colonize new areas following disturbance

(Section 1.2.). A network of horse trails on the fan may increase the spread of invasive species through manure and transmission in hooves (Wells and Lauenroth 2007). Furthermore, two gravel roads, Marquis Hole Rd. and Hay Barn Rd., cut through Blakiston Fan. These roads likely act as a corridor for invasive species as seeds can be carried on the undercarriage of vehicles (Menuz and Kettenring 2013).

Table 4. Invasive species observed on Blakiston Fan, Waterton Lakes National Park, Alberta in August 2017.

Scientific Name	Common Name	Priority of Concern*
Centaurea stoebe	Spotted knapweed	High
Centaurea diffusa	Diffuse knapweed	High
Linaria vulgaris	Common toadflax	High
Cirsium arvense	Canada thistle	Medium
Verbascum thapsus	Common mullein	Medium
Silene vulgaris	Bladder campion	Low

* As defined by Musto and Watt 2016

2.3.2. Climate Change

Precipitation is the primary climate variable in predicting the distribution of invasive plants (Bradley et al. 2009). Bioclimatic envelope modeling predicted a shift in the range of spotted knapweed to higher elevations throughout the foothills of the Rocky Mountains, leading to expansion in distribution in some areas and constriction in others (Bradley et al. 2009). When modelled under 10 future climate scenarios, 17% of currently invaded areas in Montana are no longer climactically viable for spotted knapweed by 2100 (Bradley et al. 2009). Furthermore, data indicate that hotter and drier sites are more vulnerable to invasion; climate change is likely to enhance these conditions on the fan (Menuz and Kettenring 2013). Milder winters lengthen the growing season which may lead to an increase in seed production (Hellmann et al. 2008). In the face of uncertain future climate conditions, the fate of knapweed on Blakiston Fan is unclear. Speculation may suggest that knapweed will continue to expand its distribution until conditions reach a critical threshold.

The response of native perennial forbs to changes in the annual average temperature and precipitation is poorly studied. Generally, where annual average temperatures are increasing, species are moving up in elevation and latitude, and populations that are unable to migrate are decreasing or extirpated (Huntley et al. 1995, Thuiller et al. 2005, Kelly and Goulden 2008, Corlett and Westcott 2013). For example, data showed an upward elevation shift in predominant tree and shrub species in a California mountain range over 30 years (Kelly and Goulden 2008). This shift was correlated with increased temperatures and decreased snowpack (Kelly and Goulden 2008). Modelling projections indicate that species in mountain regions are at greatest risk of extirpation (Thuiller et al. 2005). Despite the potential for migration of native forbs in response to climate change, most species will be unable to migrate at a rate equal to the rate of annual average temperature change (Corlett and Westcott 2013). In addition, observations of changes in plant phenology are expected to continue with ongoing climate variation (Menzel et al. 2006, Cleland et al. 2007). The response of native vegetation on Blakiston Fan to climate change is unclear; however, plants will likely shift to earlier phenology and attempt to migrate up in elevation. These projected changes are likely to limit food availability for the hairstreak.

Changes in annual average temperature and precipitation as a result of climate change are expected to have an effect on the phenology, distribution, and diversity of Leptidopterans (Parmesan 1996, Roy and Sparks 2000, Conrad et al. 2004). Model predictions (in the absence of confounding factors) indicated that a one degree rise in annual average temperature will lead to an advance of two to ten days in first and peak emergence of on-wing univoltine Lepidopterans (Roy and Sparks 2000). Increases in annual average temperatures are correlated with a shift in Lepidoptera species distribution to higher latitudes and altitudes across North America; host-plant availability and natural barriers limit changes in distribution (Parmesan 1996). Analysis of a 35-year dataset of 338 Leptidoptera species indicated species that fly in summer and autumn had the greatest average population decreases compared to those that fly during other seasons (Conrad et al. 2004). Similarly, analysis of a 35-year dataset of 159 species in northern California revealed a decrease in species richness at lower elevations and a general upward shift in elevation of species (Forister et al. 2010).

The above literature support the speculation that phenology and distribution of the hairstreak and its host plants will likely change with climate. If the shift in phenology and distribution of the butterfly and its host plants are largely offset, the Blakiston Fan hairstreak population will likely be extirpated. Along with changes in the vegetation community and butterfly populations, climate change is expected to increase the frequency of natural disturbances due to more extreme temperature and precipitation patterns (IPCC 2007).

2.3.3. Natural Disturbances

Blakiston Fan is influenced by two primary natural disturbances: change in river course and fire. Large spring flood events can lead to a shift in the course of Blakiston Creek. The frequency of these large flood events is influenced by winter snowpack and rate of spring melt, both of which vary with seasonal temperature and precipitation trends (Mote et al. 2005, Mote 2006, Stewart 2009). Over the past century, hydrographs of Rocky Mountain rivers shifted to earlier and lower peak flows, and largely reduced summer and early fall flows (Stewart et al. 2005, Rood et al. 2008, Stewart 2009). These trends are expected to continue as regional temperature and precipitation patterns shift with climate change (Rood et al. 2008, Stewart 2009). Changes to the course of Blakiston Creek and extended periods of low flows exposes sediments of newly abandoned channels; this disturbance generates conditions that are prone to rapid colonization by invasive species (Menuz and Kettenring 2013).

Wildfires, such as the Kenow fire, are frequently associated with a warm spring and a subsequent long, dry summer that leads to low fuel moisture (Johnson and Wowchuk 1993, Morgan et al. 2008); positive Pacific Decadal Oscillation is also associated with large fire years (Morgan et al. 2008). The fire severity (i.e., change in aboveground and belowground biomass as a result of fire) is influenced by the amount and distribution of fuel (i.e., desiccated vegetation), soil moisture, and substrate type (Keeley 2009). The level of disturbance to the vegetation community resulting from a fire depends on the fire severity (Keeley 2009). If aboveground biomass is lost, but belowground plant structures are unaffected, perennial plants will likely return the following growing season (Davis et al. 1993). Climate model projections paired with analysis of historic fire trends suggest that large fire years will likely increase in frequency throughout the Rocky Mountain region (Johnson and Wowchuk 1993, Morgan et al. 2008). Natural disturbance by a wildfire exposes an area to colonization by invasive species (Menuz and Kettenring 2013). This disturbance may also present a risk to both larval and adult hairstreaks, as well as, the native larval and nectar host plants on which they rely (Section 4.2.).

2.4. Desired Future Conditions

Desired future conditions of Blakiston Fan focus on the native vegetation community, management of invasive species, and the resilience of the hairstreak population. Increased abundance, cover, and consistent distribution of native forbs are desired to provide adequate larval and adult food sources and shelter for the hairstreak. Along with greater abundance, increased evenness across the two larval host plants and three nectar host plants will elevate the resilience of the hairstreak in the face of climate change by providing functional redundancy. Furthermore, low abundance and cover of invasive species is important to limit competition with native vegetation. Knapweed management will likely continue to be a challenge on this site; however, desired future conditions include decreased knapweed abundance to the point where minimal management interventions are required.

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Chapter 3. Experimental Control of Spotted Knapweed on Blakiston Fan

3.1. Introduction

This pilot study aims to assess the interaction between the endangered half-moon hairstreak and the primary methods of spotted knapweed management employed on Blakiston Fan. The goal of this within-season study is to assess the effects of herbicide and two timings of manual removal on within-season changes in cover of spotted knapweed and silky lupine within critical habitat of the hairstreak. Although it is not possible to assess the direct effect of these treatments on the hairstreak, this study aims to examine the effects on the primary larval host plant of the hairstreak, silky lupine. This study may be valuable in identifying the method that is most effective at decreasing the cover of spotted knapweed, while also having minimal impact on silky lupine.

3.2. Methods

3.2.1. Experimental Design

A randomized complete block design was used to examine the effect of broad-leaf herbicide (H), mid-June manual removal (M1), and late-July manual removal (M2) on spotted knapweed and non-target native forbs. Experimental units (6 x 6 m) were grouped into six blocks based on location (Figure 9). Treatments (H, M1, M2, and control) were randomly assigned with stratification to one experimental unit within each block (i.e., one replicate of each treatment in each block). A 1-m treatment buffer was applied to all treatments to decrease edge effects. Control units were walked through to mimic the level of disturbance in herbicide and manual removal units.

Aminopyralid (Milestone®, Dow AgroSciences, Calgary, AB) was applied to herbicide units via spot application using a backpack sprayer in mid-June, 2017. Most spotted knapweed plants were bolted with few remaining rosettes. Herbicide treated units received between 6.5 and 9 L of 0.05% aminopyralid (present as triisopropanolamine salt) with Xiameter® OFX-0309 surfactant (Dow Corning Canada, Mississauga, ON), and blue dye (Table 5). Two-to-three backpack sprayers were used with an approximate completion time of 10 minutes per experimental unit. Each spotted knapweed plant was sprayed until covered, but not to the point of runoff. Due care was taken to reduce contact with non-target forbs. Block 4 was removed from the study as it was deemed unsuitable site conditions for chemical application due to coarse sediments and close proximity to Blakiston Creek (i.e., < 30 m).

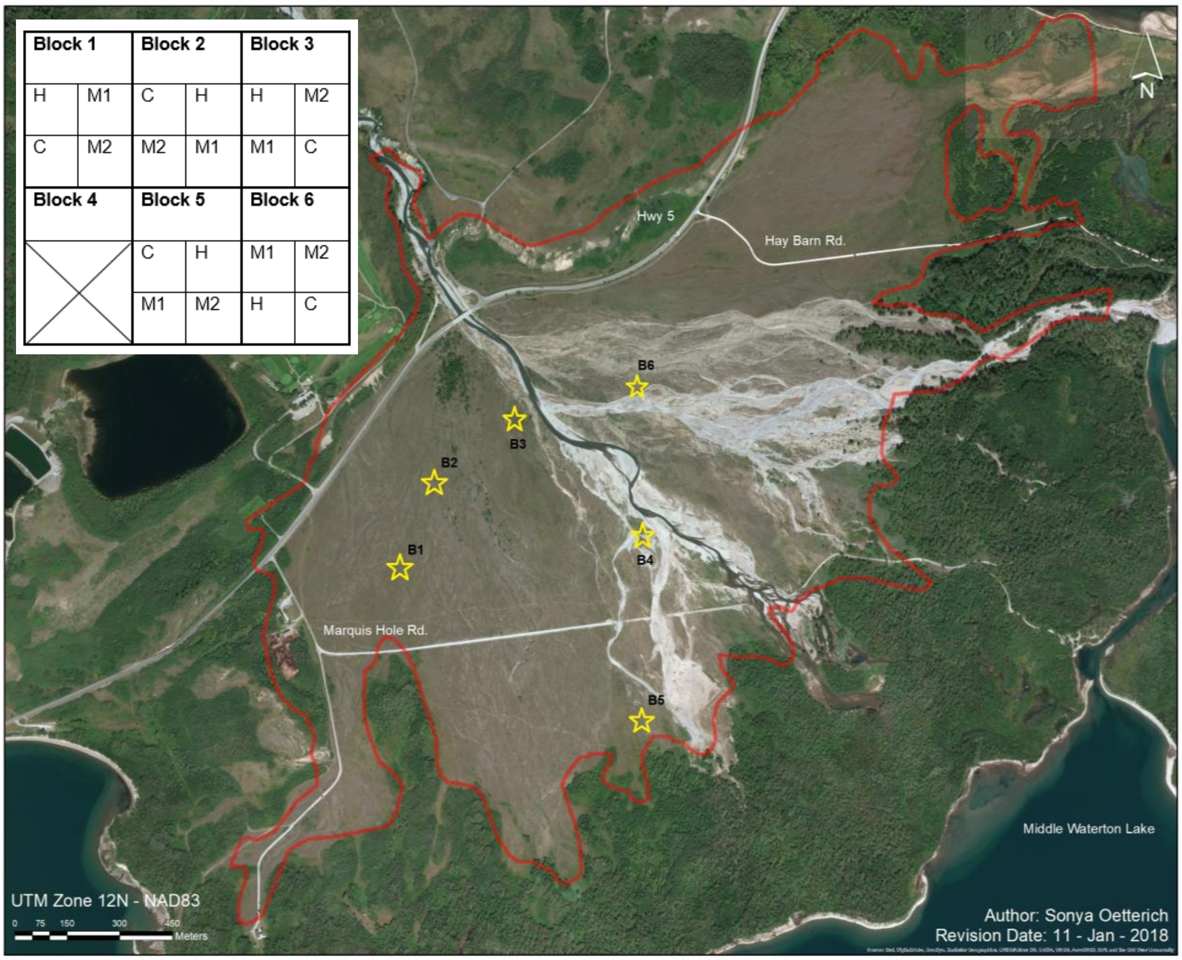

Figure 9. Approximate location of blocks (yellow star) on Blakiston Fan (Waterton Lakes National Park, Alberta). Red outline delineates area mapped as critical habitat for the half-moon hairstreak butterfly (*Satyrium semiluna*). Inset table shows the relative arrangement of randomly stratified treatments within each block. Block 4 was excluded from the experiment.

Manual removal treatments were applied at two different points in the growing season. The mid-June treatment (M1) was applied to align with timing of herbicide application. The late-July treatment (M2) was applied to align with the timing of typical operations in W.L.N.P. Spotted knapweed plants were only removed if bolted and > 10 cm in height; when pulling anything smaller there is very low chance of removing the perennial taproot. Due attention was taken to remove as much of the taproot as possible. Tools were not used to minimize soil disturbance. Gloves were worn when handling spotted knapweed as it can cause contact dermatitis and skin irritation (Bhowmik 2005). Harvested plant material was collected into heavy duty garbage bags and removed from site for safe disposal. Time of completion of knapweed removal with a single labourer varied from 1.5 to 3 hours depending on the density of knapweed, substrate type, and distribution relative to native vegetation.

Table 5. Date of treatment application and volume of herbicide applied on Blakiston fan, Waterton Lakes National Park, Alberta. All controls were first measured on June 21st, 2017.

Block*	Herbicide	Volume Herbicide Applied (L)	Manual 1	Manual 2
1	19-Jun-17	8	23-Jun-17	27-Jul-17
2	19-Jun-17	6.5	22-Jun-17	26-Jul-17
3	19-Jun-17	9	22-Jun-17	25-Jul-17
5	19-Jun-17	8	21-Jun-17	24-Jul-17
6	15-Jun-17	8	21-Jun-17	24-Jul-17

* Block 4 removed from experiment.

3.2.2. Block Selection

Block locations were selected based on trends in vegetation distribution (Tannas and Tannas 2009; Tannas 2013) and soil classification (Canada Department of Agriculture 1973). All blocks are within the Blakiston Creek zone of influence (i.e., within the alluvial fan) in areas that the hairstreak has been observed (Kondla and Smith 2009) (Appendix E). Corners of experimental units were marked with a metal rod and GPS coordinates (UTM) were collected for the northeastern corner. To avoid confounding variables, all experimental units were ≥ 50 m from biological control release sites. Repeated annual surveys conducted by Parks Canada confirm that biocontrol agents are not yet established in the area, thus are not expected to have an effect on treatments. Experimental units were ≥ 10 m from areas treated with herbicide in 2016 to minimize effects of former treatments. All blocks contain spotted knapweed. Soil type, predominant substrate, groundcover characteristics, and predominant native vegetation vary between blocks (Table 6). All blocks have a slope of 0 to 5%.

Table 6**.** Abiotic and biotic characteristics of experimental blocks on Blaksiton Fan, Waterton Lakes National Park, Alberta.

Block	Soil Type	Substrate and Groundcover	Predominant Native Vegetation
1	Orthic dark brown chemozoic	Lichen and moss Occasional boulders (>256 mm)	Lupines (*Lupinus*) Milkvetches (*Astralagus spp.*)
2	Orthic dark brown chemozoic	Lichens and moss Occasional boulders	Lupines Western paintbrush (*Castilleja occidentalis*)
3	Orthic eutric brunisol	Thick grass	Graminoids Occasional lupine
4*	Orthic dark brown chemozoic	Boulders Cobbles (65 – 256 mm) Pebbles (2 – 64 mm) Woody debris	Wolfwillow (*Elaeagnus commutata*) Lupine rare
5	Orthic and cumulic regosols	Many bare patches	Milkvetches
6	Orthic dark brown chemozoic	Lichens Cobbles	Lupines Stonecrop (*Sedum lanceolatum*)

* This block was not used in the experiment due to high porosity and < 30 m from Blakiston Creek.

3.2.3. Sampling

Prior to applying treatments, vegetation within each experimental unit was sampled using a 0.25-m^2 quadrat (0.5 x 0.5 m). Six sampling plots were randomly stratified throughout each experimental unit. A 1% circular tile (diameter = 0.056 m) was used as a reference point to minimize observer error. Percent cover measurements were collected for spotted knapweed, silky and silvery lupine, sulphur-flower and yellow buckwheat, other forbs, and other shrubs (specific species were recorded if cover was > 10%); percent cover of bare ground, and woody debris/rocks (> 20 mm) were also recorded. Sampling was repeated two weeks after applying treatments to examine changes in cover relative to control plots. End-of-season sampling was conducted during the last week of August, 2017.

3.2.4. Data Analysis

Change in percent cover was calculated by subtracting cover before treatment from cover after treatment. Subsamples were averaged to produce an arithmetic mean for each experimental unit. 95% confidence intervals were calculated using standard deviation. Brown and Forsythe test was used to test for homoscedasticity as opposed to the traditional Levene's test because the distribution was skewed (Brown and Forsythe 1974). Data was non-normal, but analysis of variance (ANOVA) is robust to violation of this assumption (Schmider et al. 2010). A two-way ANOVA was used to examine: 1) among blocks, 2) among treatments, and 3) block by treatment interactions of change in percent cover two-weeks post-treatment (Table 7). A Tukey's Honest Significant Difference (H.S.D.) post hoc was used to identify the source of significant differences ($\alpha = 0.05$).

Silky lupine was not present in the H unit of Block 5 and the M1 unit of Block 2. In order to avoid an unbalanced design, the average value for that treatment was used for each missing value. Assumptions of homoscedasticity remained satisfied after this change. The same two-way ANOVA was applied to silky lupine data.

Table 7. Analysis of variance table: n = 5, k = 4, and m = 6 where *n* is the number of blocks, *k* is the number of treatments, and *m* is the number of subsamples.

Source	Formula	Degrees of Freedom
Block	n-1	4
Treatment	k-1	3
Block x Treatment Interaction	(n-1) (k-1)	4*3 = 12
Error	kn(m-1)	4*5*(6-1) = 100
Total	knm-1	(4*5*6)-1 = 119

3.3. Results

Percent cover of spotted knapweed in experimental plots before-treatment ranged from 5.53% (± 1.98) to 13.13% (± 4.63); lupine cover ranged from 4.97% (± 2.79) to 12.00% (± 4.29) (Figure 10). The range in percent cover of both plants in plots before treatment is likely due to variations in timing of the first measurement during the field season. Knapweed cover dropped below 1% in herbicide and second manual treatment plots two weeks post-treatment, with an average cover of 0.45% (± 0.19) and 0.15% (± 0.15), respectively.

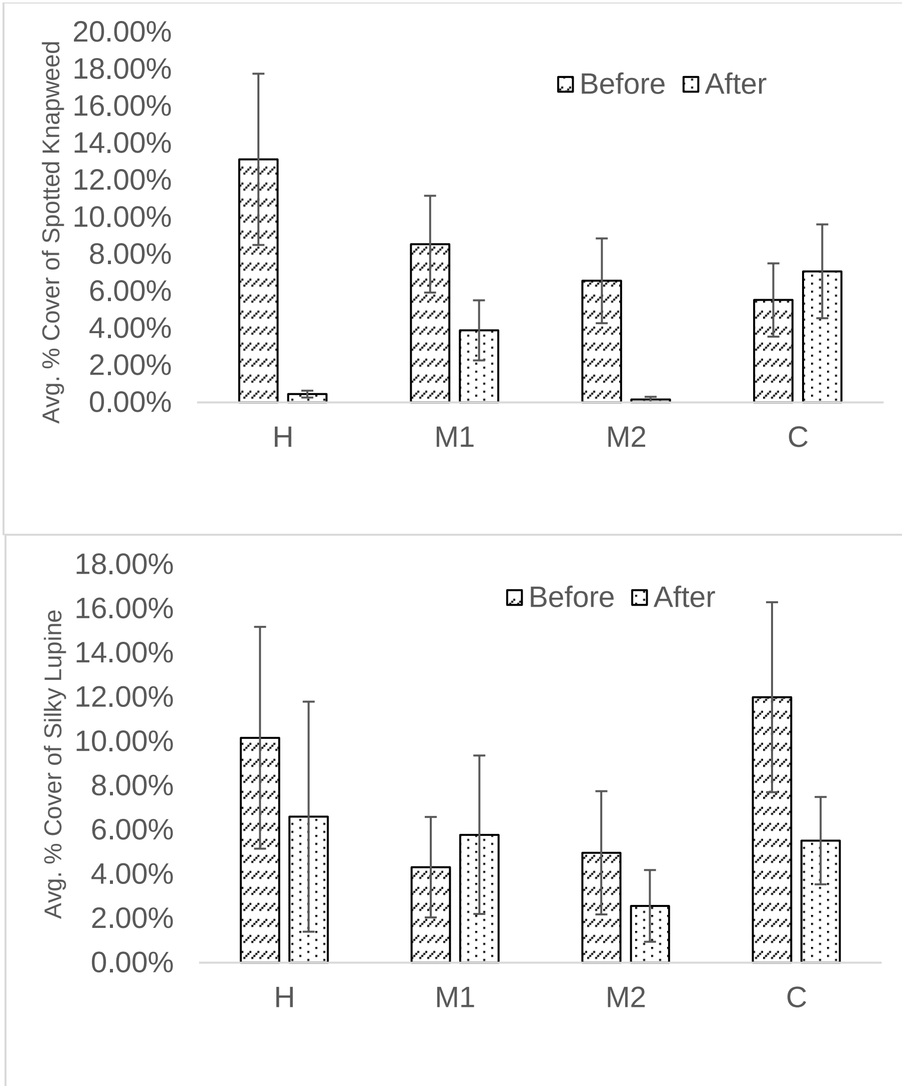

Figure 10. Average (± 95% CI) percent cover of spotted knapweed (top) and silky lupine (bottom) pre- and two weeks post-treatment by treatment. Treatments were: herbicide (H), mid-June manual removal (M1), late-July manual removal (M2), and control (C). Data collected on Blaksiton Fan (Waterton Lakes National Park, Alberta) in summer, 2017. Before and after treatment cover data by block and treatment combination are supplied in Appendix F.

Herbicide plots showed an average decrease of 12.70% (± 5.53) in percent cover of knapweed two weeks post-treatment. Knapweed cover increased 1.60% (± 2.62) on average in control plots. The first and second manual treatments saw an average decrease in cover of 4.70% (± 3.11) and 6.40% (± 2.56), respectively.

Herbicide plots showed an average decrease of 4.46% (± 9.49) in percent cover of lupine two weeks post-treatment. Lupine cover increased following the first manual treatment by an average of 1.83% (± 7.06), whereas, the second manual treatment saw an average decrease in cover of 2.40% (± 4.12). Lupine percent cover decreased 6.48% (± 6.56) on average in control plots.

Significant treatment effects ($p = 0.006$, $f_{3, 12} = 6.89$) were seen in the change in percent cover of spotted knapweed two weeks post-treatment (Figure 11). A Tukey's H.S.D. post hoc test revealed a significant difference between herbicide and control treatments. There was no significant difference in the change in lupine percent cover among treatments ($p = 0.075$, $f_{3, 12} = 2.96$).

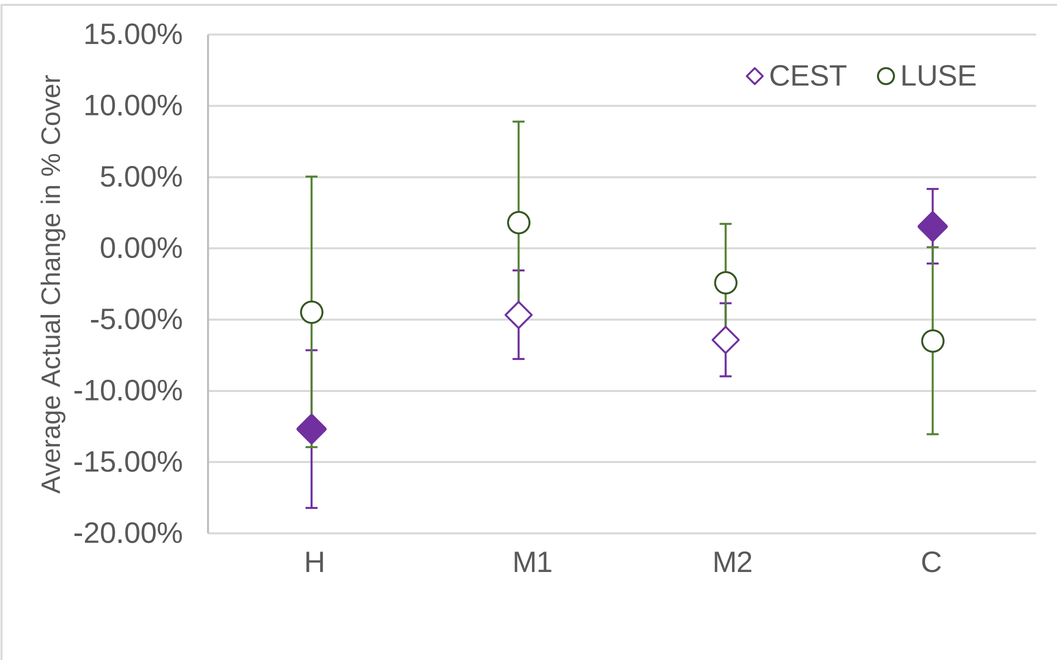

Figure 11. Average (± 95% CI) actual change in percent cover of spotted knapweed (triangle; CEST) and silky lupine (circle; LUSE) two weeks post-treatment. Treatments were: herbicide (H), June manual removal (M1), July manual removal (M2), and control (C). All CEST treatments and M2 and C LUSE treatments had a sample size of five (n=5). LUSE treatments H and M1 had a sample size of four (n=4). Solid points indicate a significant difference. Data collected on Blaksiton Fan (Waterton Lakes National Park, Alberta) in summer, 2017.

3.4. Discussion

A significant difference was observed in the response of spotted knapweed to herbicide treatment when compared to control. Herbicide treatment was expected to have the greatest short-term effects on knapweed cover based on the literature (Section 1.2.4.). The biological significance of this finding cannot be confirmed based on these data as this is a within-season study with a small sample size; long-term data are needed to accurately assess the biological effects of these treatments.

A significant difference in lupine cover was not observed in response to different treatments. This suggests that management strategies used in this study may not have a significant within-season effect on larval host plants of the hairstreak. However, conclusions as to the effect of these treatments on native vegetation over the long-term, or even multiple growing seasons cannot be made. Nectar host plants of the hairstreak were not included in the data analysis. The data were insufficient to analyze the within-season effects of treatments on nectar host plants due to their late phenology and patchy distribution across the fan.

Desiccation likely accounts for a large proportion of the difference seen among treatments because the before treatment measurements were taken at different points throughout the season immediately prior to application of the treatment. To better account for desiccation, pre-treatment measures should be made at the same time regardless of when the treatment is applied. In addition, desiccation can be accounted for through multiple seasons of experimental observation.

Lastly, observations indicate that the timing of manual removal has an influence on the amount of knapweed removed. The timing of the first manual removal was likely too early; at least a quarter of the knapweed individuals had not bolted or stems were too small to effectively be removed. The later timing of manual removal was able to target a higher proportion of knapweed plants. Some plants were seed set leading to concerns of spreading seeds during removal. Manual removal must be appropriately timed to ensure the largest proportion of plants can be removed while maintain a low risk of seed dispersal.

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Chapter 4. Post Fire Restoration

Rigorous monitoring is an important component of the restoration of Blakiston Fan. The first growing season following the Kenow fire on Blakiston Fan will provide important insights into the likely response of the vegetation community and the hairstreak to the fire. Expected responses can be inferred from literature, but data are required to assess the accuracy of predicted responses. The direction of succession will largely guide the route for restoration. A triaged management approach will be effective in managing knapweed and maintaining the native vegetation community for the remaining hairstreak population. This chapter will: 1) outline a monitoring plan to assess the post-fire vegetation community and the relative abundance of the half-moon hairstreak on Blakiston Fan; 2) provide an assessment of the expected ecosystem response to the fire grounded in literature; and 3) provide recommendations for post-fire management of the vegetation community and hairstreak population.

4.1. Monitoring Plan

The proposed monitoring plan for Blakiston Fan focuses on tracking changes in the relative abundance of the hairstreak, vegetation monitoring in unburned areas, and post-fire revegetation in burned areas. Changes in average annual temperature and precipitation in response to climate change are expected to continue to alter the phenology of plants and insects (Parmesan 1996, Roy and Sparks 2000, Conrad et al. 2004, Thuiller et al. 2005, Corlett and Westcott 2013). Long-term tracking of the phenology of native nectar host plants is needed due to the observed association between blooming of nectar host plants and the emergence of adult hairstreaks (B.C. Southern Interior Invertebrates Recovery Team 2011).

Monitoring is important to determine the status of the hairstreak population on Blakiston Fan following a burn. Butterfly surveys are recommended during the summer of 2018 and should be repeated annually for five to ten years to determine the change in relative abundance of hairstreaks. Repeated monitoring over a five to ten year period can capture the interannual variability of the population over multiple generations to gain a better understanding of the Blakiston hairstreak population status (Gordienko and Sokolov 2009). Following the annual monitoring period, butterfly surveys are recommended every two-to-four years; this enables long-term tracking of population changes (Schmucki et al. 2016). Interannual population fluctuations may decrease as the climate continues to warm; however, smaller populations are prone to greater fluctuations (Oliver et al. 2012). Greater variability in population growth rates increases the probability of extinction (Inchausti and Halley 2003). Given this information, more frequent monitoring may be needed to assess the status of the species.

Pollard walks conducted in summer of 2017 showed a relatively low detection rate of adult hairstreaks relative to meandering surveys (Section 2.2.); this may be due to the lack of continuity in the distribution of native larval and nectar host plants. Meandering surveys are recommended to increase detectability. Date, start and end time, surveyors, survey track (recorded on GPS), and location of hairstreak observations should be recorded during surveys. Surveyors must be familiar with the behavioural and morphological differences between the hairstreak and butterflies similar in appearance to decrease the likelihood of false identification (Appendix B). Practice and training can be done during probing surveys and using preserved specimens. Probing surveys should commence at timing of yellow buckwheat bloom (i.e., mid-to-late July). The timing of probing surveys may be modified over time as the emergence of nectar plants is influenced by spring temperatures; earlier spring onset and warmer temperatures will likely result in earlier hairstreak emergence (Gordienko and Sokolov 2009).

Monitoring of the vegetation community across Blakiston Fan is important in guiding the direction of restoration. Survey methods developed by Tannas and Tannas (2009) are intensive and time consuming. Regardless, continuation of these methods enables long-term tracking of changes in distribution and cover of spotted knapweed and native vegetation. To decrease the resources and time demands while maintaining comparability between survey years, a modified survey is recommended. This modified method involves using existing transects and polygon locations established by Tannas and Tannas (2009), but monitoring odd numbered transects and plots in odd numbered years and even numbered transects and plots in even years. Mapping analysis of changes in knapweed distribution is an important component of this monitoring. Mapping is recommended at the end of each summer to guide knapweed management practices and prioritize areas for the following season.

4.2. Predicted Post Fire Response

Monitoring the revegetation in burned areas and changes in unburned areas is key in prioritizing restoration actions on Blakiston Fan. In the interim, literature should be used to determine the most likely short-term post-fire response of the vegetation community and the hairstreak. Restoration and management recommendations may need adjustment to address unexpected conditions as data are collected.

Natural disturbances such as the Kenow fire are expected to increase in frequency due to climate change (Section 2.3.3.); this will likely increase the challenge of managing the Blakiston Fan vegetation community. Fire creates conditions that are favourable for rapid revegetation by invasive species, such as spotted knapweed (Sheley et al. 1998). Native forbs and graminoids typically revegetate burned sites to pre-burn conditions two-to-three years post-fire (Antos et al. 1983, Tracy and Mcnaughton 1997, Turner et al. 2003, Gucker and Bunting 2011). The response of the hairstreak population to the Kenow fire is unclear. Due to the heterogeneity of the burn across the fan, groups of larvae may remain intact. The timing and magnitude of native and invasive revegetation in the first growing season will be influenced by seasonal precipitation and temperature trends. This response is important in determining the likely succession of the vegetation community and the fate of the hairstreak on Blakiston Fan.

Although low intensity fire kills the aboveground biomass of knapweed, it does not affect the perennial taproot and the seedbank (Davis et al. 1993). Average seed germination of spotted knapweed was significantly higher in soils of burned sites than unburned sites (Wolfson et al. 2005). Furthermore, soil moisture content and soil temperatures were higher following a burn than in unburned plots; these factors may play a role in increased seed germination (Wolfson et al. 2005). Alternatively, there was a 95% decrease in knapweed seed germination when exposed to a grassland fire with a fuel load of 200 g/m^2 (Vermeire and Rinella 2009). There may be insufficient fuel to reach this fire severity due to the distribution of vegetation across Blakiston Fan. Investigation into the fuel load is needed to address this speculation. Furthermore, a 95% reduction in seed germination may be insufficient as it still can result in 250 to 2000 germinated seeds (Schirman 1981). A similar species of knapweed, yellow starthistle, returned to unburned levels three years post-fire (Gucker and Bunting 2011). Knapweed cover across Blakiston Fan is expected to return to pre-fire conditions and will likely increase due to fire-germinated seeds.

The predicted response of native vegetation to the Kenow fire will focus on vegetation community changes post-fire throughout the Rocky Mountains region and the Pacific Northwest. Generally, low severity fires during late summer have little effect on altering the composition of the vegetation community as most predominant species are summer dormant (Antos et al. 1983, Tracy and Mcnaughton 1997, Gucker and Bunting 2011). Carbohydrate stores in roots enable sprouting of perennial vegetation during the first growing season post-fire with seed production two years later (Turner et al. 2003). In many cases, native and non-native graminoids and forbs recover to pre-fire conditions or greater within three years (Antos et al. 1983, Tracy and Mcnaughton 1997, Turner et al. 2003, Gucker and Bunting 2011). There is minimal research into the long-term (i.e., > 5 years) post-fire response of grasslands of the P.N.W. Although cover of moss and lichen recovered three years post-fire, the community composition is largely altered (Antos et al. 1983). The post-fire response of lupines on Blakiston Fan will likely be positive in the short-term. A study of an Idaho grassland saw a significant increase in silky lupine cover three years post-fire compared to unburned plots (Gucker and Bunting 2011). Similarly, burned grassland plots showed a significantly greater aboveground biomass of silky lupine one and five years post-burn compared to unburned plots (Tracy and Mcnaughton 1997).

There is very little literature investigating the response of Lepidopterans to fire. However, Thom et al. (2015) present a comprehensive field and lab study of pupa survival under various locations and fire temperature conditions. The alta hairstreak (*Eumaeus atala*) is an endangered Florida butterfly restricted to fire-prone ecosystems where its host plant is found (Thom et al. 2015). Similar to the half-moon hairstreak, pupae of the alta hairstreak live at the base of their host plant or in the leaf litter (B.C. Southern Interior Invertebrates Recovery Team 2011; Thom et al. 2015). Lab experiments examined the temperature and duration of heat pulses while field experiments tested pupa survival at a range of soil depths (Thom et al. 2015). Complete mortality was observed in pupa at the soil surface and survival was positively correlated with soil depth; survival was defined as adult emergence within 30 days of treatment. (Thom et al. 2015). Fire temperatures are highest where combustion occurs (i.e., burning of organic matter), thus complete mortality of larvae and eggs on host plants is expected due to a thermal threshold of 50°C (Whelan 1995, Thom et al. 2015). There are likely surviving individuals in unburned areas of the fan that can act as a source for population persistence. Conversely, high frequency fires will likely lead to the extirpation of the hairstreak.

Overall, knapweed cover is expected to return to pre-burn conditions and will likely increase initially across Blakiston Fan. The native vegetation community is expected to recover to pre-burn conditions two-to-three years post-fire. Alternatively, the lichen and moss community is not expected to return to pre-burn conditions in the short-term (i.e., < 5 years). The hairstreak population is expected to persist in the short-term; however, the frequency of fire on site and the vegetation community response will play an important role in the long-term population viability. Restoration recommendations focus on areas where hairstreaks have recently been observed, unburned areas, and areas with lower cover of knapweed and relatively high cover of native host plants.

4.3. Restoration Recommendations

Recommendations for restoration of the native vegetation community on Blakiston Fan aim to target the control of spotted knapweed and the regeneration of larval and nectar host plants of the hairstreak. Historical and current data of the adult hairstreak distribution and relative abundance on the fan is used to triage zones for restoration. The primary assumptions of these recommendation are: 1) limitation of larval and nectar host plant is the primary cause of the decline of the hairstreak population; 2) expansion of spotted knapweed is associated with the decreased distribution and cover of native plants; and 3) a source population of hairstreaks persists on Blakiston Fan following the 2017 Kenow fire. Blakiston Fan has been divided into three primary management units (Figure 12). Restoration recommendations are triaged and designated to specific management units to concentrate efforts where they may have the greatest effect in supporting the hairstreak and limiting knapweed distribution (Table 8).

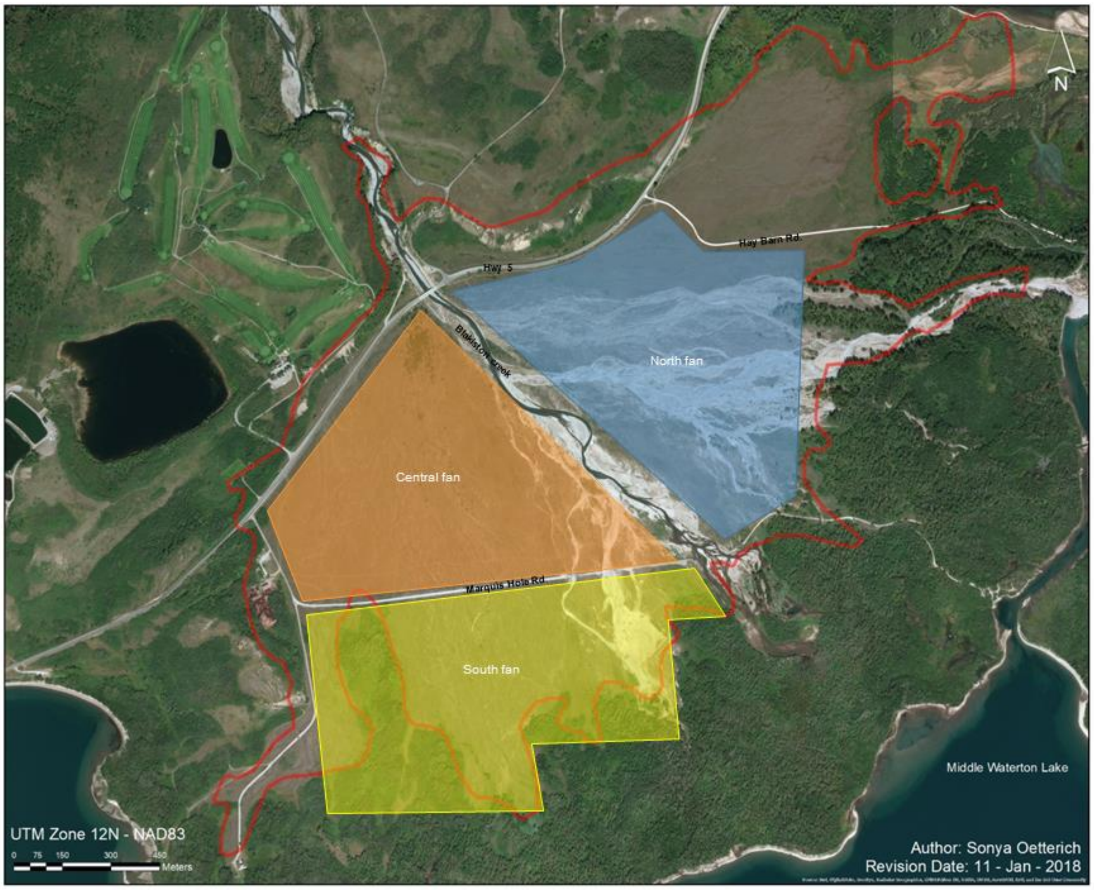

Figure 12. Proposed management units for Blakiston Fan, Waterton Lakes National Park, Alberta: North fan (blue), central fan (orange), south fan (yellow). Red outline shows critical habitat of the half-moon hairstreak (*Satyrium semiluna*).

4.3.1. South Fan Management Unit

The south fan is the recommended priority for restoration of native host plants and rigorous control of knapweed. This area has consistently shown suitable habitat conditions for the hairstreak including a relatively low knapweed cover and consistent distribution of native host plants. A high proportion of the distribution of hairstreak observations are concentrated in the south fan (Section 2.2.). In addition, large areas of the south fan were not burned during the 2017 fire. Due to this combination of factors, the south fan is recommended to be the top priority for restoration action. Recommendations specific to the south fan management unit are three-fold: 1) intensive and highly selective herbicide application to decrease knapweed and limit its expansion; 2) protect the area against further anthropogenic disturbances; and 3) implement a long-term native planting experiment. Maintaining the integrity of the vegetation community in the south fan is important to ensuring the persistence of the hairstreak, particularly in the first growing season post-fire.

Table 8. Summary of restoration recommendations for Blakiston Fan (Waterton Lakes National Park, Alberta).

Recommendation	Objective	Management Unit(s)	Timing	Long-term
Intensive and selective control of knapweed.	To decrease cover and limit the expansion of knapweed	South	Summer 2018 onward	Monitoring of effectiveness and continued management
Closure of horse trails and restricted site access during hairstreak emergence.	To decrease physical impacts on nectar host plants and transmission of invasive species	South	Mid-July to mid-August annually	Revegetation of fallow trails
Repeated biological control releases as needed	To establish root-boring and seed head feeding biocontrol for long-term control of spotted knapweed	Central and North	Ongoing	Monitoring of biocontrol populations and effectiveness
Application of herbicide (Milestone) to monoculture patches of knapweed.	To significantly reduce the cover of knapweed and individuals reproducing	Central and North	Annually in late-spring /early-summer and fall	Monitoring of effectiveness and continued management
Pilot study of experimental planting and seeding of native larval and nectar host plants	To examine the viability of active restoration of hairstreak-associated vegetation using a pilot study	South	Summer 2019	Large scale implementation of native revegetation if successful
Complete mapping of horse trails and subsequent limitation of their extent	To decrease the physical impacts and transmission of invasive species	All	Summer 2019	Enforcement to ensure adherence to trail closures

Selective herbicide application is recommended on the south fan to decrease the cover and distribution of spotted knapweed. The distribution of knapweed is relatively patchy and frequently mixed among native vegetation, thus targeted application is important to ensure the persistence of native host plants. Manual removal is recommended in areas with a high frequency of native larval and nectar host plants. Mid-summer application of manual removal is recommended (i.e., after bolting, but before full seed set).

Horses act as a vector for transporting invasive species (Wells and Lauenroth 2007). Complete mapping of horse trails across Blakiston Fan would allow comparison to vegetation surveys to assess the relative risk of horse trails acting as a corridor for invasive species. Closure of horse trails through the south fan is highly recommended as a pro-active measure to decrease the inputs of invasive species to the areas prioritized for knapweed control. In addition, limiting manual removal on the south fan during the bloom of nectar host plants is recommended. This will limit the potential physical impact of trampling nectar host plants during the emergence of adult hairstreaks.

A small-scale planting and seeding experiment is recommended on the south fan. This would enable an assessment of the feasibility of active restoration of native larval and nectar host plants to areas from which they have been extirpated following knapweed control. Monitoring of post-fire revegetation is important to determine the value of such an experiment. Passive restoration of target vegetation may be preferred if they are able to effectively colonize the site naturally.

4.3.2. Central and North Fan Management Units

Management of the central and north fan is recommended to focus on the control of knapweed monocultures and limit the expansion of knapweed. Biological control is recommended as a long-term management strategy. Herbicide application is needed in high knapweed areas with low native vegetation.

Biological control (i.e., biocontrol) is the use of pathogens and parasites to control invasive species (Müller-Schärer and Schroeder 1993). Thirteen insect species have been used as biocontrol agents for spotted knapweed in North America, these insects can be classified into two groups: seed-head feeders and root borers (Wilson and Randall 2005). Multiple biocontrol agents can often be used simultaneously due to their specific feeding behaviours (Knochel et al. 2010, Bourchier and Crowe 2011). Data indicate that *Larinus minutus* and *Cyphocleonus achates* have an additive negative effect on knapweed biomass and flower production (Knochel et al. 2010, Bourchier and Crowe 2011). Introductions to establish these species are recommended for the long-term management of knapweed on the north and central fan.

Larinus minutus (Curculionidae) is a univoltine seed head-feeding weevil that reduces the density of spotted knapweed (Wilson and Randall 2005). Females selectively oviposit on open flowers of *Centaurea* spp.; all members of this genus are non-native plants from Eurasia (Jordan 1995). Larvae feed on the achenes of knapweed during a four-week development phase (Wilson and Randall 2005). A single larva can render a seed head non-viable (Jordan 1995, Kashefi and Sobhian 1998). New adults emerge in mid-to-late summer and feed-heavily on the vegetative structures of knapweed (Kashefi and Sobhian 1998). Adults overwinter in leaf litter at the base of host plants (Kashefi and Sobhian 1998). Although *L. minutus* is effective at reducing spotted knapweed densities, there is a considerable time-lapse between introduction and time of effects observed (Wilson and Randall 2005, Van Hezewijk and Bourchier 2011). Van Hezewijk & Bourchier (2011) found that despite an increase in weevil density and distribution, spotted knapweed densities continued to increase five years post-introduction. Story et al. (2008) studied changes in seed production of spotted knapweed, seeds in soil, and the density and distribution of five biocontrol agents introduced into western Montana over 30 years. *Larinus* spp took over a decade to establish. Once established, *Larinus* spp. had the greatest effect in reducing seeds per seed head (Story et al. 2008). This 30-year study indicates the promising effects of seed head-feeding weevils as a long-term tool for the management of spotted knapweed.

Cyphocleonus achates (Curculionidae) is the most commonly used root-boring weevil for the biocontrol of spotted knapweed in North America (Wilson and Randall 2005). *C. achates* larvae feed on root tissue and can reduce knapweed vigor or lead to plant death (Corn et al. 2006). Story et al. (2006) saw a significant decrease in spotted knapweed density 11 years post-introduction with significant increases in weevil density after 5 years. Alternatively, data indicate the population of *C. achates* is highly dependent on the density of knapweed as populations are limited by availability of root material for consumption (Corn et al. 2006). Additionally, larval consumption of root tissue may increase the drought sensitivity of spotted knapweed, a highly drought-tolerant species (Corn et al. 2006). This weevil is best suited for decreasing the vigor of high density spotted knapweed plots in areas of low-moisture soils, such as Blakiston Fan.

Biological control is an effective long-term method for the control of spotted knapweed with seed head-feeding weevils targeting the seed source and root-boring weevils reducing the vigor of the perennial part of the plant. However, biocontrol is not an immediate control method, thus should be a part of a long-term knapweed management strategy for Blakiston Fan.

Herbicide application (Milestone®) is recommended in areas of knapweed monocultures throughout the north and central fan. Literature (Section 1.2.4.), as well as, data from this within-season study demonstrated the effectiveness of herbicide application in the short-term control of spotted knapweed (Section 3.3.). Continued spring to early-summer application and fall application of herbicide is recommended for the immediate control of knapweed, particularly in large monocultures and areas with no hairstreak observations. In addition, continued manual removal is recommended, particularly in areas along Blakiston Creek where herbicide application is not permitted.

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Appendix A. Vegetation Survey Methods

Vegetation surveys were conducted from August 8th to 17th, 2017 after the completion of half-moon hairstreak surveys. Species of interest in this vegetation survey were the five native larval and nectar host plants of the half-moon hairstreak, spotted knapweed (*Centaurea stoebe*), and other invasive species present. Native larval and nectar host plants include: silky lupine (*Lupinus sericeus*) and silvery lupine (*L. argenteus*), yellow buckwheat (*Eriogonum flavum*), sulphur-flower buckwheat (*E. umbellatum*), and Missouri goldenrod (*Solidago missouriensis*), respectively. Methods were replicated from the 2008 and 2013 surveys (Tannas and Tannas 2009; Tannas 2013). Eighteen north-south transects were established at 50-m intervals across Blakiston Fan between Hwy 5 and the southern tree line. GPS coordinates were used to locate sampling points. The centre-point of radial polygons (diameter = 50 m) were established at 50-m intervals along each transect. Visual assessment was conducted while walking through the polygon from north to south in a zig-zag pattern. A time range of 4-6 minutes per polygon was defined to standardize sampling effort. Up to two distribution density classes were recorded for each species of interest within each polygon. Distribution density classes were assigned based on percent cover midpoints expected within a grassland community (Table A1) (Tannas 2013). All species observed throughout the fan were recorded to compile a complete species list.

Average percent cover of each species per transect was calculated using cover midpoints associated with each distribution density. A GIS overlay was used to model changes in the cover of spotted knapweed from 2013 to 2017. Mapping was used to compare the distribution of native nectar and larval host plants to the distribution of the half-moon hairstreak.

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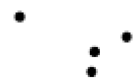
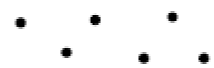
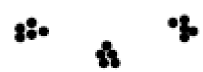
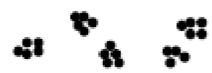
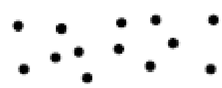
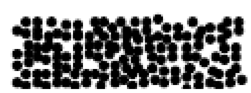
Table A1. Density distribution classes with estimated percent cover for grassland communities (Tannas 2013).

Density Distribution			Percent Cover	
Class	**Description of Abundance**	**Distribution**	**Estimated Cover Class**	**Range**
1	Rare individual, a single occurrence		0.5%	0.01 – 1%
2	A few sporadically occurring individual plants		0.5%	0.01 – 1%
3	A single patch or clump of species		1%	0.5 – 2%
4	Several sporadically occurring plants		4%	1 – 10%
5	A few patches		4%	1 – 10%
6	Several well-spaced patches		10%	5 – 20%
7	Continuous uniform occurrences of well-spaced plants		10%	5 – 20%
8	Continuous occurrences of plants with a few gaps in distribution		30%	20 – 45%
9	Continuous dense occurrence of plants		50%	35 – 70%
10	Non-continuous population with one or more satellite population(s)		30%	15 – 45%

Appendix B. Half-moon Hairstreak Survey Methods

Pollard walks were conducted July 26th, 27th, 30th, 31st and August 1st and 3rd, 2017 in accordance with methods outlined by Kondla and Smith (2009) to estimate relative abundance of adult half-moon hairstreaks. Preliminary surveys were conducted July 21st and 24th, 2017 by meandering through areas of suitable habitat identifying butterflies in flight and perching. Suitable habitat is defined as areas with little grass and patches of *Eriogonum* spp and *Lupinus* spp (Kondla and Smith 2009). Timing of preliminary surveys was selected based on plant phenology. Hairstreaks typically begin to emerge when *Eriogonum* spp are in bloom and *Lupinus* spp have set seed (Kondla and Smith 2009).

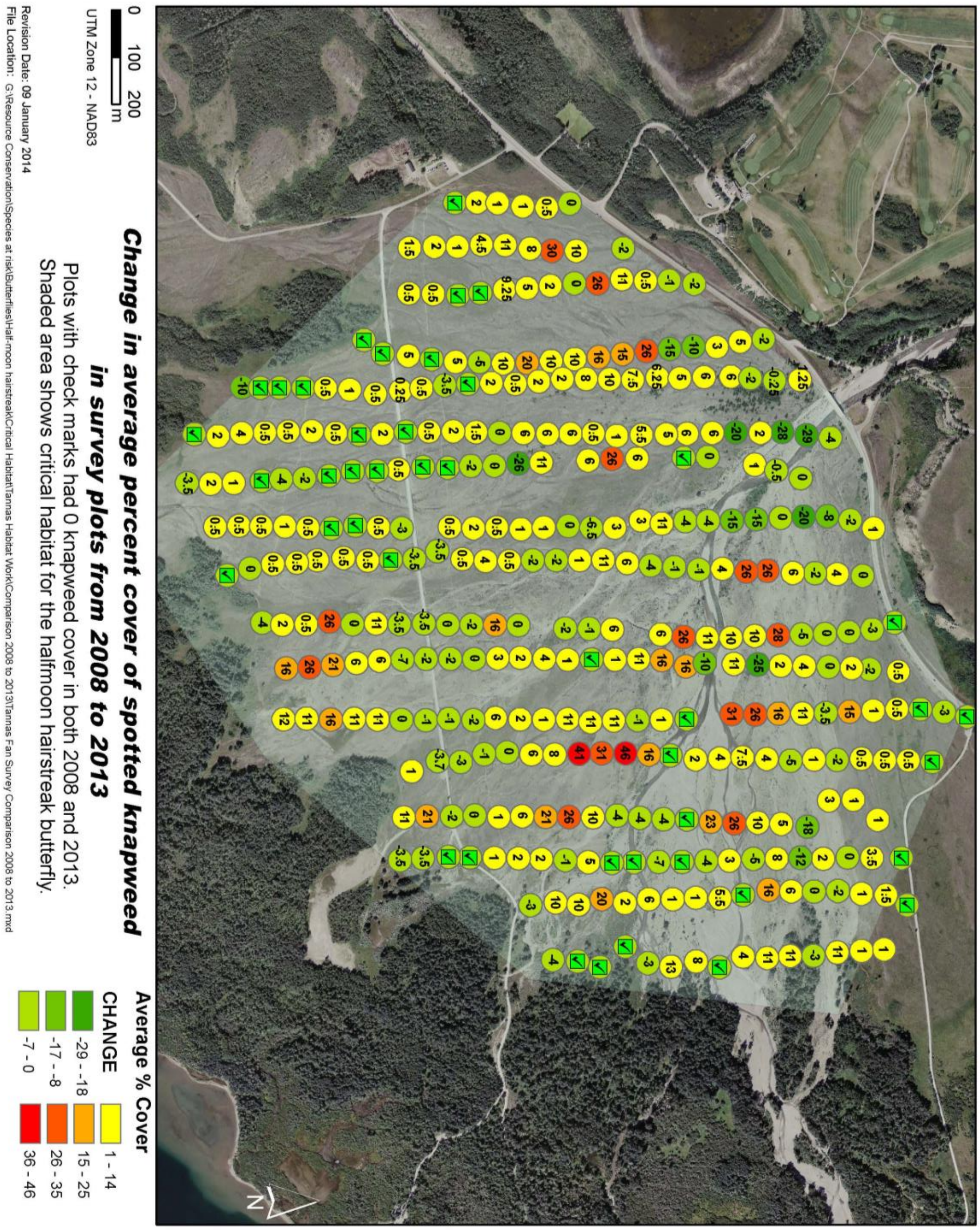
Fifty-four 150-m transects were randomly scattered across Blakiston Fan in areas of suitable habitat. Each transect took 5 to 10 minutes to walk at a steady pace. Transects were cut short and distance recorded if no suitable habitat was observed. Surveys were conducted between 10h and 17h when temperatures were above 17°C with little cloud cover. Wind was not a factor as hairstreaks have been observed regardless of wind conditions (Kondla and Smith 2009). Two observers were used to increase detectability. Observations were made within 3-m on each side of a transect. This is smaller than the 5-m observation radius defined by Pollard (1977) to increase the detectability of this smaller species (Kondla and Smith 2009). The first recorder focused on navigation and the second recorded observations and meandered through the transect strip. Data recorded includes: transect ID, start and end time, waypoints, and hairstreak adults counted; changes in weather conditions were also noted. Boisduval's blue (*Plebejus icarioides*) and Melissa blue (*Plebejus melissa*) can be mistaken for the half-moon hairstreak (Kondla and Smith 2009). Morphological and behavioural differences were used to distinguish the half-moon hairstreak from the blues (Table B1).

Meandering surveys were also employed in areas of suitable habitat throughout the survey period. These surveys yielded higher detectability and require lower sampling effort, but greater expertise in spotting and identifying individuals. When possible, the location of observations were recorded along with wing wear.

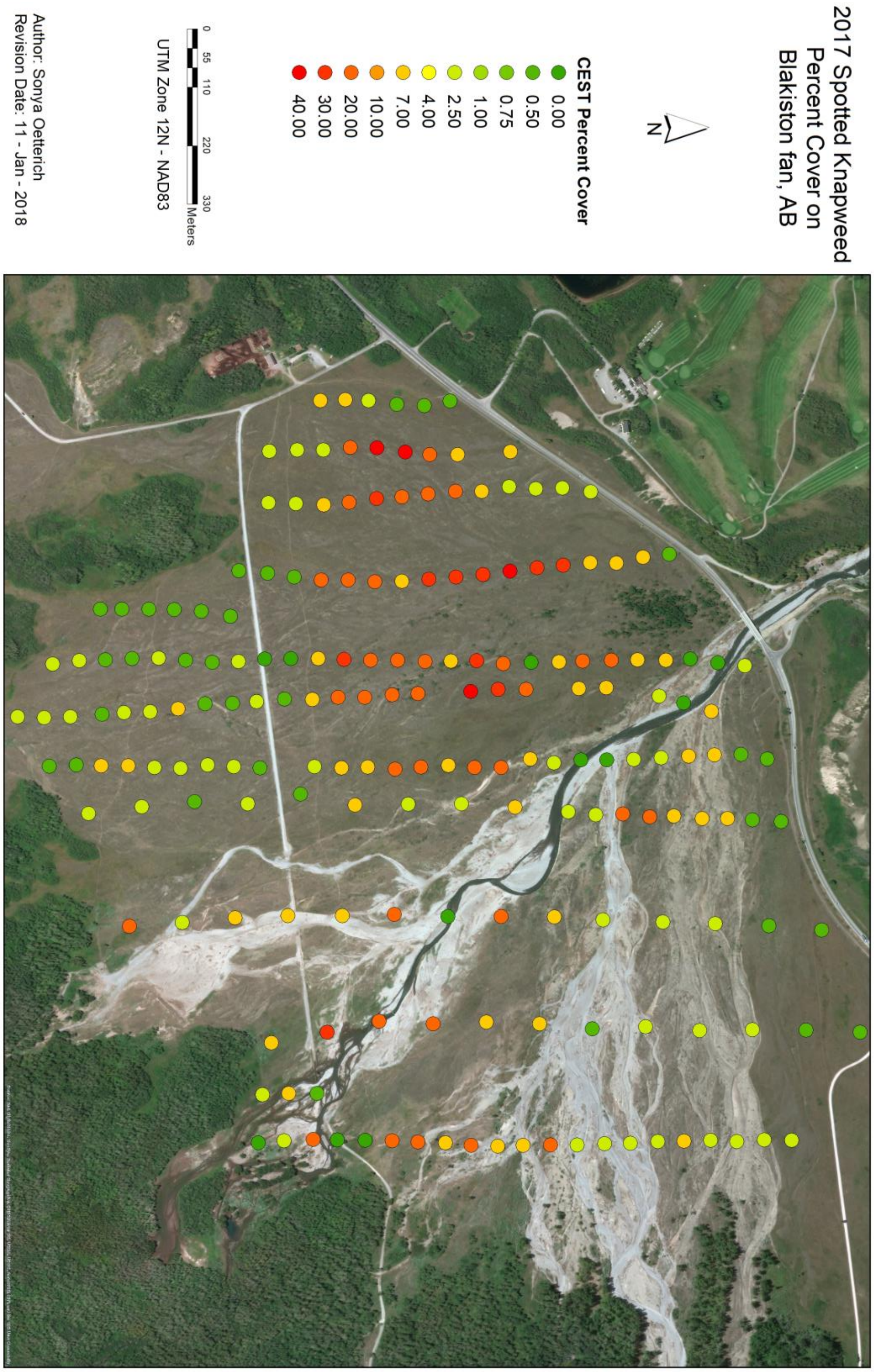
Table B1. Morphological and behavioural characteristics used to distinguish the half-moon hairstreak from blues.

Morphological / Behavioural Characteristic	**Half-moon hairstreak (*Satyrium semilunar*)**	**Boisduval's blue (*Plebejus icarioides*)**	**Melissa blue (*Plebejus melissa*)**
Ventral wing spots	Faint, in arch along forewing.	Distinct; black to brown; darker on forewing.	Distinct; yellow-orange; larger along margin of the hind wing, smaller on fore wing.
Dorsal wing colouration	Grey-brown (♀ and ♂).	Grey-brown with orange spots along hindwing margins (♀). Royal blue with thick black margins (♂).	Blue-black with yellow-orange spots along margins (♀). Royal blue with thin black margins (♂).
Wing shape (when perching)	Angular, pointed.	Heart-shaped, rounded.	Heart-shaped, rounded.
Perching behaviour	Never open wings. Crawl across flower head.	Open wings in low wind conditions.	Rub wings together. Open wings in low wind conditions.
Flight	Short and direct, typically to nearest flower head. Relatively sedentary.	Fluttery, indirect. Easily startled into flight.	Fluttery, indirect. Easily startled into flight.

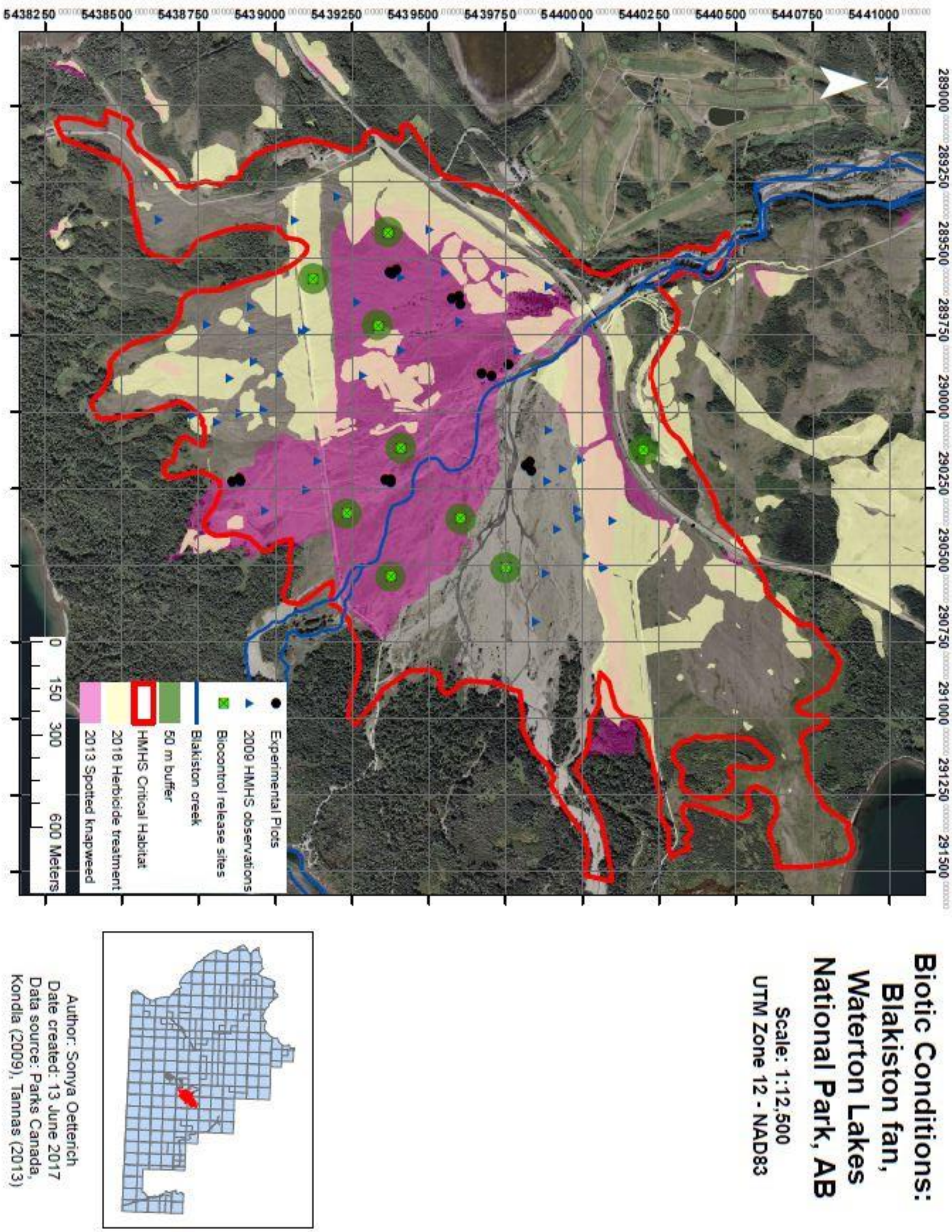
Appendix C. Change in Percent Cover of Spotted Knapweed on Blakiston Fan from 2008 to 2013

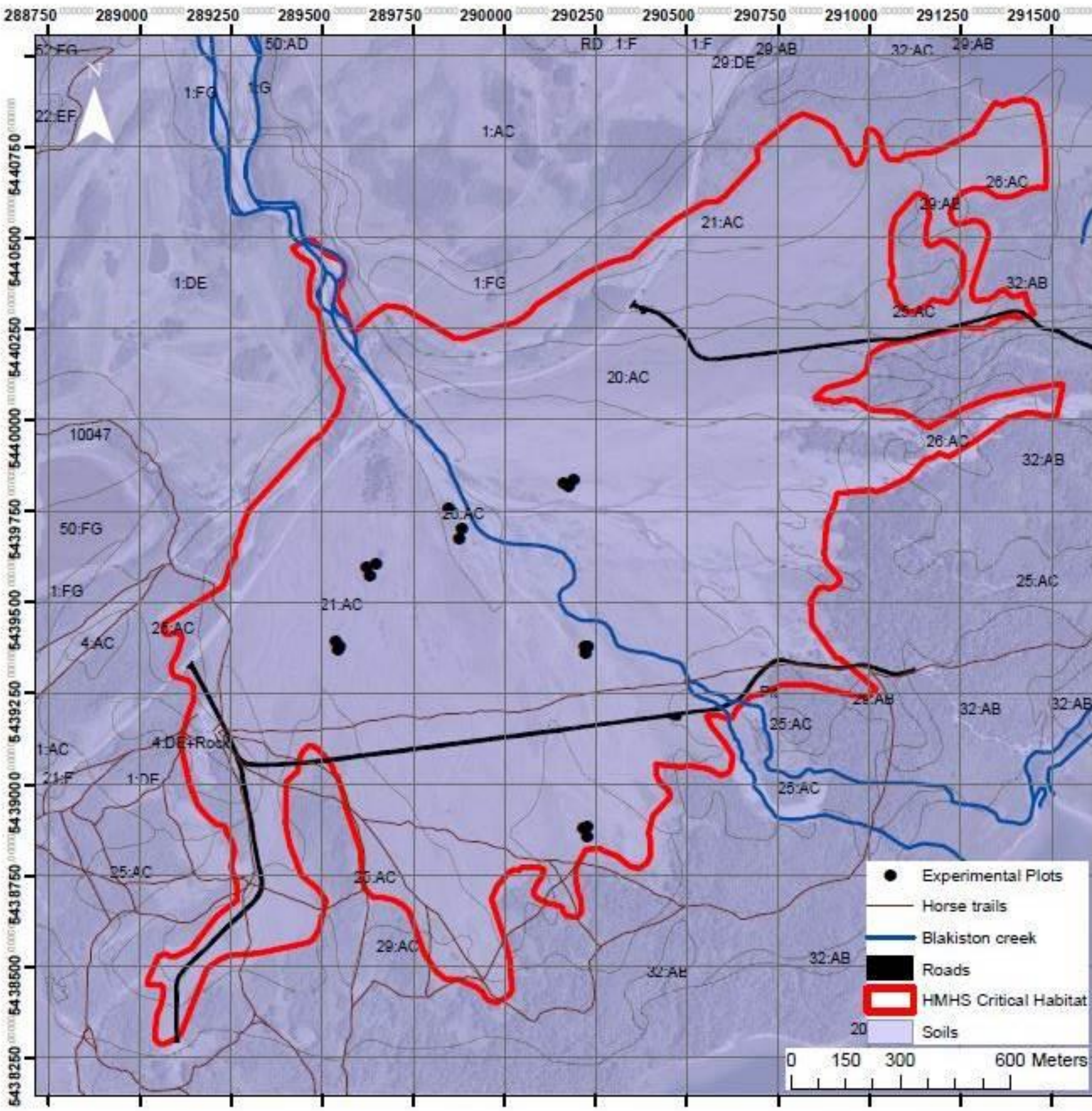


Appendix D. 2017 Spotted Knapweed Cover



Appendix E. Biotic and Abiotic Conditions Maps





Abiotic Conditions: Blakiston fan, Waterton Lakes National Park, AB

Scale: 1:12,500
UTM Zone 12 - NAD83

Soil Classification

Map Unit	Subgroup Classification	Parent Material and Texture	Landforms
1	Orthic Dark Brown and Orthic Black Chernozemics	Very coarse texture, gravelly and sandy outwash	Glaciofluvial terraces, eskers, kames, outwash plains
4	Lithic Orthic Brown Chernozemic		
20	Orthic Regosol	Alluvium, 5 to 95% coarse fragments (>2mm), and sand to loam texture	Alluvial fans
21	Orthic Dark Brown Chernozemic		
25	Orthic and Cumulic Regosols		
26	Orthic Eutric Brunisol		
29	Gleyed Cumulic Regosol		
32	Orthic Humic Gleysol		

Topography

Class	Slope (%)
A	0 – 0.5
B	0.5 – 2
C	2 – 5
D	5 – 9
E	9 – 15
F	15 – 30
G	30 – 60
H	>60

Author: Sonya Oetterich
Date created: 13 June 2017
Data source: Parks Canada, Canada Department of Agriculture (1973)

Appendix F. Experimental Data by Block and Treatment Combination

Table F1. Average percent cover of spotted knapweed (*Centaurea stoebe*) by block and treatment combination, before and two weeks post-treatment on Blakiston Fan (Waterton Lakes National Park, Alberta).

CEST	B1		B2		B3		B5		B6	
	Before	After	Before	After	Before	After	Before	After	Before	After
H	12.67	0.13	6.50	1.10	31.00	0.05	12.00	0.37	3.50	0.60
M1	8.08	8.17	8.33	4.02	18.00	1.25	3.17	1.03	5.17	5.00
M2	6.50	0.08	4.52	0.00	14.83	0.35	3.17	0.00	3.83	0.33
C	5.67	10.17	4.33	4.33	7.83	9.33	6.50	8.42	3.33	3.17

Table F2. Average percent cover of silky lupine (*Lupinus sericeus*) by block and treatment combination, before and two weeks post-treatment on Blakiston Fan (Waterton Lakes National Park, Alberta).

LUSE	B1		B2		B3		B5		B6	
	Before	After	Before	After	Before	After	Before	After	Before	After
H	7.67	2.50	3.17	0.00	9.33	3.00	-	-	30.67	27.50
M1	3.58	2.08	-	-	5.83	7.67	0.33	3.33	11.83	15.83
M2	4.50	3.17	1.00	0.17	2.17	0.00	0.00	2.17	17.17	7.33
C	8.33	4.42	0.50	0.33	12.00	2.58	6.50	8.33	32.67	11.92