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The Decline of Diffuse Knapweed in British Columbia

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Ministry of Forests and Range
Forest Science Program

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R.F. Newman, S. Turner, B.M. Wallace, and
S. Cesselli

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ABSTRACT

There are literature reports of a decline in diffuse knapweed population beginning in the early 2000s at several locations on western North American rangeland. To document changes in certain diffuse knapweed populations in British Columbia, we selected five previously monitored diffuse knapweed–invaded sites located on low-elevation grasslands in the Bunchgrass and Ponderosa Pine BEC zones in the southern interior and sampled these for plant species cover, and abundance of biological control insects. Diffuse knapweed populations and soil seed reserves were shown to decline by an average of 74% and 78%, respectively, at five sites in British Columbia from the 1990s to 2009. Three factors were discussed as possible causes for the decline of diffuse knapweed at the five sites. Climate warming/drying was shown to have occurred over the same period as the reported decline in diffuse knapweed at three Kamloops sites and is a possible contributing factor. Increased plant competition, particularly from bluebunch wheatgrass, may also be a contributing factor; however, the small number of sampling sites in this study cannot provide firm conclusions in this regard. The ubiquitous nature of biological control insects at the five sites, combined with their known abilities to damage knapweed, also places biological control as a possible contributing factor for the decline of diffuse knapweed. It is also possible that two or more of the three factors are acting in concert to reduce diffuse knapweed. The demonstrated decrease in diffuse knapweed at the five sampled sites provides baseline data that may contribute to a better understanding of how biological control agents, climate warming/drying, and improved grazing management may be interacting on weed-invaded sites in British Columbia.

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1 INTRODUCTION

Invasive plants on North American rangelands have altered ecosystems by reducing forage used by livestock and wildlife, and by altering ecological processes, such as hydrological and nutrient cycles (Masters and Sheley 2001; Duncan et al. 2004). Diffuse knapweed (*Centaurea diffusa* Lam.) is perhaps the most well-known invasive rangeland plant in western Canada and the United States. The earliest record of this plant was in 1907 from an alfalfa field in Washington state, and the species was first observed in British Columbia in the early 1930s (Howell 1959). By 1974 this invasive alien plant had spread into an estimated 30 000 ha of British Columbia's open habitat, primarily in the southern interior, including grasslands, open forests, roadsides, and other disturbed areas (Watson and Renney 1974; Maxwell et al. 1992). Current estimates of its range are approximately 63 400 ha in British Columbia (IAPP 2010). However, plant size and density have declined noticeably since about 2001, as reported at several sites in the southern interior of British Columbia (Myers 2007; Myers et al. 2009) and as observed at some locations (Figure 1).

To date, diffuse knapweed has caused enormous economic and environmental damage in British Columbia. The economic impact is primarily due to its devastating effect on native bunchgrasses, a valuable resource for the ranching sector. Harris and Cranston (1979) reported that diffuse knapweed reduced forage production by more than 88%. The total economic loss in British Columbia from a reduction in recreation values and available forage, and an increase in soil erosion was estimated at $22 million (Frid et al. 2009). The successful proliferation of diffuse knapweed is primarily due to its ability to thrive in seasonally-dry environments combined with its high reproductive capacity (Watson and Renney 1974). Native plant species decline in vigour and are out-competed at knapweed-invaded sites because diffuse knapweed starts growing early in the spring and depletes much of the available soil moisture (Sheley et al. 1998). Diffuse knapweed not only invades disturbed environments, but also can affect pristine plant communities (Wikeem et al. 1986; Lacey et al. 1990). Diffuse knapweed occupies 14 of the 16 Biogeoclimatic Ecosystem Classification (BEC) (Meidinger and Pojar 1991) zones in British Columbia (IAPP 2010) and has the ability to influence a wide range of plant communities.

A biological control program for knapweed in British Columbia was initiated in 1970 with the goal to reduce diffuse knapweed populations and encourage recovery of native rangeland species with the intention of achieving low levels of the invasive plant and healthy populations of desirable species. This led to the importation of 12 insects for diffuse and spotted knapweed combined, and successful establishment of 10 biological control agents, seven of which are relatively common on diffuse knapweed (Appendix 1). Two species of fungi are also known to attack knapweed, one of which is considered native, the other adventive (i.e., locally or temporarily naturalized). Subsequent biological control agent release efforts primarily by the B.C. Ministry of Forests and Range (BCMFR) and the B.C. Ministry of Agriculture in the past 40+ years have been aggressive, with a total of 1317 and 2304 biological control releases for diffuse and spotted knapweed, respectively (IAPP 2010). Diffuse knapweed has been reported to be in decline at some sites in the United States (Seastedt et al. 2003, 2007; Coombs et al. 2004; Smith 2004) and Canada (Myers et al. 2009). Effects of herbivory from multiple biological control insects (Seastedt et al. 2007; Knochel and Seastedt 2010), increased resource competition from native plant species as a result of improved grazing management (Jacobs and Sheley 1998; Sheley et al. 1998) and effects of an extended period of drought during the last few decades (Corn et al. 2007; Pearson and Fletcher 2008) have been proposed as mechanisms for the decline. This technical report provides documentation of long-term monitoring of diffuse knapweed-invaded plant communities at five selected sites in the southern interior of British Columbia and provides a discussion of the possible reasons for the observed decline in British Columbia.

FIGURE 1 *Diffuse knapweed-invaded site on July 16, 1997 before release of the biological control insect,* Larinus minutus *(top photo) and 4 years later showing reduction of diffuse knapweed (bottom photo), near Rock Creek, B.C.*

2 METHODS

To document the observed changes in diffuse knapweed populations, we selected five previously monitored sites that contained diffuse knapweed located on low-elevation grasslands in the Bunchgrass and Ponderosa Pine BEC zones in the southern interior of British Columbia. The sites selected had plant community data as far back as 39 years taken along permanently established transect lines. These permanent transects were established between 1970 and 1993, and had been re-measured between 2 and 6 times (Table 1). All new plant and insect sampling occurred during June 15–18, 2009. Three of the five sites were located near Kamloops (Batchelor, Long Lake, Prudens) and one each near Penticton (White Lake) and Summerland. Most sites had received moderate-to-heavy grazing by cattle and/or horses over the past 16–39 years. At the Prudens site there are both grazed and ungrazed plant community data over a 39-year period. Grazed and ungrazed areas at Prudens were sampled separately, resulting in a total of six data sets.

The Daubenmire canopy coverage method was used to determine the percentage cover of all vascular plant species at each site within 48 or 50, 20 × 50 cm plots located along permanent transects (Daubenmire 1959). Plant frequency was calculated as the proportion of sampled plots per site containing a particular plant species. Data on diffuse knapweed soil seed banks were included from three additional sites near Kamloops (Table 2). These seed bank sites are within 80 m–3 km of the Prudens site and within the same pasture management unit. The soil seed bank was re-sampled on these sites for diffuse knapweed seeds to a depth of 2.2 cm using ten 5-cm diameter cores per site (Newman 1998). Cores were processed individually after air-drying by using a series of sieves, followed by direct counting under a dissecting microscope. Seeds were assumed to be viable if they were plump and well filled, had an unbroken seed coat, and were firm with slight pressure.

Diffuse knapweed plants at the five vegetation monitoring sites also were sampled for evidence of biological control insects. Plants sampled were offset by at least 5 m from the vegetation transects to avoid damage to the permanent plots. Mature 2-year-old plants with the current season's growth (or previous-year plants when live plants were not available) were chosen to examine for evidence of previous insect agent presence. Where diffuse knapweed plants were frequent, a systematic-random method was used to select 50 sample plants located along fixed transects. Where diffuse knapweed was infrequent, the closest 50 plants to the vegetation sampling transects were sampled. Plants were first checked for adult insects present on the exterior. Height, from the soil surface to the tip of the uppermost seed head of the erect plant, was measured for each sample plant. Plants were then excavated in the field and the roots assessed for immature stages of the insects and evidence of their damage. Four seed heads were randomly collected from each plant (total 200 per site) and dissected in the laboratory while viewing with a hand lens and a dissecting microscope, when necessary, to determine existing species and numbers present.

2.1 Data Analysis

Data on knapweed abundance over time and the types of biological control insects at the five sites are presented using descriptive statistics with standard errors provided when the mean is based on more than one sample (year or site).

Simple linear regression was used to determine if relationships existed between diffuse knapweed frequency and height, and the percentage of biological control insect occurrence by site. Regression was also used to test for a relationship between diffuse knapweed and bluebunch wheatgrass by site. Simple linear and second-degree polynomial models were tested using the SAS procedure REG (SAS Institute Incorporated 2003).

TABLE 1 *Diffuse knapweed sites in southern interior British Columbia, re-sampled in 2009*

Site	Elev. (m)	BEC unit	Latitude / Longitude	Years sampled
Batchelor	690	BG xw1	50°45' N/120°25' W	93, 95, 97, 01, 09
Long Lake	762	BG xw1	50°47' N/120°24' W	92, 94, 96, 01, 09
Prudens grazed	697	BG xw1	50°45' N/120°25' W	70, 81, 86, 91, 96, 08, 09
Prudens ungrazed	697	BG xw1	50°45' N/120°25' W	70, 81, 86, 91, 96, 09
Summerland	432	PP xh1	49°33' N/119°38' W	86, 91, 09
White Lake	551	PP xh1a	49°19' N/119°37' W	87, 91, 92, 94, 95, 09

TABLE 2 *Diffuse knapweed soil seed bank sites near Kamloops, B.C., re-sampled in 2009*

Site	Elev. (m)	BEC unit	Latitude / Longitude	Years sampled
Redhill	710	BG xh1	50°45' N/120°24' W	95, 09
Racetrack	670	BG xh1	50°45' N/120°25' W	95, 09
Stinking lake	708	BG xh1	50°45' N/120°24' W	95, 09

3 RESULTS AND DISCUSSION

3.1 Diffuse Knapweed Frequency

Field sampling in 2009 confirmed that diffuse knapweed is in decline at the five sites (Table 3). The frequency of sample plots containing diffuse knapweed dropped from 79.3±7.8% in the 1990s to 21.2±8.2% in 2009, a 74.4±9.9% overall reduction. Diffuse knapweed frequency decreased at each of the five sites by a minimum of 40.5% and the species was virtually eliminated at two sites, Prudens ungrazed and Summerland (Table 3). This represents a significant change because diffuse knapweed has not been recorded below 42% frequency at any of the sampled sites since 1981.

The three Kamloops sites, considered as a group, provided sufficient permanent sampling points across years to discern the pattern of invasion and decline over the last four decades in the area. No diffuse knapweed was recorded at the earliest sampling date in 1970 at the Kamloops sites; however, by the early 1980s diffuse knapweed was present in 52% of the 146 sampled plots (Figure 2). By 1986, knapweed had reached its peak infestation at >90%. These high levels of infestation were maintained until at least 1997, after which they started a steep decline. The decline of diffuse knapweed at all five sites in this study is in agreement with the trend reported in other studies. Diffuse knapweed cover, stem density, and seed production was reduced in a Colorado grassland (Seastedt et al. 2003). Similarly, Myers et al. (2009) reported a decline of diffuse knapweed at four sites in the southern interior of British Columbia.

TABLE 3 *Mean diffuse knapweed frequency in the 1990s compared to 2009 at five sites in southern interior British Columbia*

	Diffuse knapweed frequency (%)		
Site	**1990–1999**	**2009**	**Change**
Batchelor	88 (2.5)[a]	13	85.2
Long Lake	88 (3.5)	27	69.3
Prudens grazed	78 (12)	36	53.8
Prudens ungrazed	96	0	100.0
Summerland	42	1	97.6
White Lake	84 (6.9)	50	40.5
Overall mean	79.3 (7.8)	21.2 (8.2)	74.4 (9.9)

a Standard error is provided in brackets following the mean when the mean is based on more than one sample (year or site).

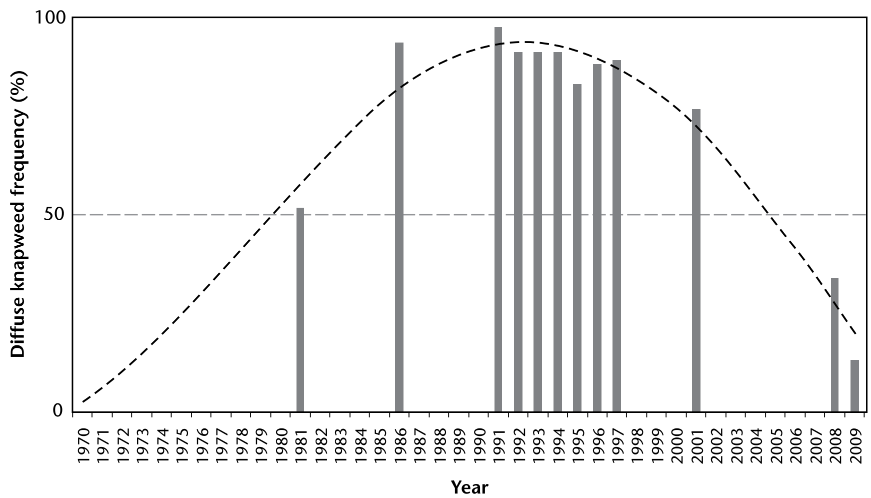

FIGURE 2 *Average frequency of diffuse knapweed at three sites near Kamloops, B.C. for 1970–2009 based on 146 total permanent plots.*

3.2 Soil Seed Bank

Soil seed bank sampling in 2009 at three Kamloops sites revealed a substantial reduction in seed density compared to 1995. The density of sound diffuse knapweed seeds dropped from 1307±148 seeds m^{-2} in 1995 to 289±103 seeds m^{-2} in 2009, a 78% reduction.

A healthy diffuse knapweed plant can produce up to 900 seeds (Watson and Renney 1974). Decades of seed production combined with seed persistence (8 years or more) can result in accumulated soil seed banks as high as

48 100 seeds m^{-2} (Risley et al. 1986; Schirman 1981). This pool of seeds creates an additional challenge when trying to manage diffuse knapweed. Even if all new seed production is curtailed there could be ongoing recruitment of knapweed plants for many years from the residual seed bank. Furthermore, Myers et al. (2009) describe simulation models that predicted that seed reduction alone is not sufficient to result in a decrease in the plant population because of compensatory seedling survival.

The decline in seeds in the soil bank at the Kamloops sites suggests that plants are either no longer contributing the same numbers of seeds due to reduced plant density or because there is a reduced number of seeds per plant, both of which have been observed at the Kamloops sites. The seed bank decline also suggests that a reduction in the contribution to the seed bank has occurred for many years because of the documented longevity of knapweed seeds in the soil (Davis et al. 1993), which tends to buffer short-term changes of seed input.

3.3 Diffuse Knapweed Height

Average measured diffuse knapweed plant height (25.7±2.9 cm) was noticeably lower than the low end of the range of heights (50–80 cm) described in Watson and Renney (1974) for this species (Table 4). It is interesting that a recent survey of diffuse knapweed in the European countries of Turkey, Romania, and Ukraine reported heights that are close to heights from this study (30.10±3.65 cm) (Blair and Hufbauer 2009).

TABLE 4 *Average height of sampled diffuse knapweed plants at five sites in southern interior British Columbia (n=50 by site, n=300 all sites)*

Site	Diffuse knapweed height (cm)
Batchelor	21.9
Long Lake	25.8
Prudens grazed	20.1
Prudens ungrazed	28.9
Summerland	37.5
White Lake	17.7
All sites	25.7 (2.9)

3.4 Biological Control

Sixty-four percent of the 300 diffuse knapweed plants sampled for biocontrol agents in 2009 displayed some evidence of insect attack. Fifteen percent of the plants showed evidence of both root and seed head attack (Table 5). The most common agent by far was *Urophora affinis*, found on 40.3% of the plants sampled. Four agents (*U. affinis, Agapeta zoegana, Cyphocleonus achates,* and *Larinus minutus*) were present to some degree at all five sites (Table 6).

C. achates abundance was weakly negatively correlated ($p = 0.12$) to knapweed height, while *A. zoegana* abundance was positively correlated ($p = 0.01$) to knapweed height. Although *C. achates* is generally associated with plants with large roots to support feeding larva (Stinson et al. 1994), the effect of the weevil attack is known to reduce spotted and diffuse knapweed biomass (Corn et al. 2006), which could explain its negative relationship with knapweed height. This relationship is also in agreement with a study from Colorado (Knochel and Seastedt 2010). *A. zoegana* is known to select large, mature host plants (Smith and Story 2003), which could explain the positive relationship with knapweed height. There were no statistically significant relationships ($p > 0.15$) found between the height of plants collected in 2009 and the combined abundance of biological control insects.

There were also no statistically significant relationships found between the frequency of diffuse knapweed and the abundance of biological control insects. This is most likely due to the timing of our sampling in relation to the pattern of diffuse knapweed decline. Using the three Kamloops sites as an example, it can be seen that insect sampling in 2009 was conducted when there would have been few vigorous host plants available (Figure 2).

TABLE 5 *Percentage (SE) of sampled diffuse knapweed plants with root-feeding and/or seed-feeding biological control insects, or evidence thereof, at five sites in southern interior British Columbia, June 15–18, 2009*

Site	Root feeding	Seed feeding	Root and seed feeding	Root or seed feeding
Batchelor	18	48	6	60
Long Lake	16	20	4	32
Prudens grazed	22	60	12	70
Prudens ungrazed	44	56	24	76
Summerland	28	84	24	88
White Lake	36	44	20	60
All sites	27.3 (4.5)	52.0 (8.6)	15.0 (3.6)	64.3 (7.8)

TABLE 6 *Percentage (SE) of sampled diffuse knapweed plants with specific biocontrol insects, or evidence thereof, at five sites in southern interior British Columbia, June 15–18, 2009*

	Biological control insect							
	Root feeding				Seed feeding			
Site	AGZO	CYAC	SPJU	PTIN	LAMI	URAF	URQU	MEPA
Batchelor	4	6	2	6	18	36	0	2
Long Lake	6	10	0	2	10	12	0	0
Prudens grazed	6	10	0	8	18	48	0	0
Prudens ungrazed	14	2	8	22	36	30	2	0
Summerland	22	2	2	2	10	76	4	0
White Lake	2	10	26	0	4	40	2	0
All sites	9.0 (3.1)	6.7 (1.6)	6.3 (4.1)	6.7 (3.3)	16.0 (4.6)	40.3 (8.7)	1.3 (0.7)	0.3 (0.3)

AGZO = *Agapeta zoegana;* CYAC = *Cyphocleonus achates;* SPJU = *Sphenoptera jugoslavica;* PTIN = *Pterolonche inspersa;* LAMI = *Larinus minutus;* URAF = *Urophora affinis;* URQU = *Urophora quadrifasciata;* MEPA = *Metzneria paucipunctella.*

3.5 Possible Mechanisms for Diffuse Knapweed Decline

Plant populations can fluctuate over time due to a number of intrinsic and extrinsic factors that can affect growth and reproduction (Harper 1977). Factors responsible for the sharp decline in abundance of diffuse knapweed in British Columbia and the western United States as suggested by Masters and Sheley (2001) include:

- changes in abiotic environmental factors such as temperature and moisture, leading to less favourable conditions for growth and reproduction;
- increased plant competition; and
- biological control by insects.

3.5.1 Changes in abiotic environmental factors It is possible that the climate has not been optimal for diffuse knapweed over the past decade, particularly at low elevations in the southern interior (Figure 3). Corn et al. (2007) hypothesized that multiple droughts in the last few decades throughout the western United States has contributed to the observed decline in spotted knapweed. This could explain both the reduction in plant frequency as well as the reduction in soil seed bank. Examination of climate data from Kamloops airport shows a warming trend for the period 1990–2009 (Figure 3). This is consistent with documented climate warming in British Columbia over the past century (Moore et al. 2008). Mean average temperature at Kamloops airport for the first decade of the 2000s was 0.25°C warmer than the previous decade (1990–1999), while the mean maximum temperature was almost 0.5°C warmer. The same period also experienced a drying trend. Precipitation from 2000 to 2009 was 89% of the long-term normal, while precipitation in the 1990s was 112% of the long-term normal.

Diffuse knapweed is adapted to semiarid areas with annual mean temperatures from 7.2–9.4°C and annual precipitation of 24.1–41.7 cm (Watson and Renney 1974). At 9.5°C, the mean annual temperature at Kamloops airport in the first decade of the 2000s was slightly warmer than the upper range for diffuse knapweed. There is a possibility that warming has resulted in temperatures near the maximum for optimal diffuse knapweed growth and reproduction at low-elevation sites. Diffuse knapweed seedlings are sensitive to growing-season drought. May/June precipitation is considered critical for seedling survival of diffuse knapweed (Myers and Berube 1983). May/June precipitation at Kamloops airport fell by 21% in the first decade of the 2000s compared to the 1990s. Schirman (1981) attributed differences in diffuse knapweed seed production at selected sites in Washington to seasonal variation in growing-season precipitation. Growing season (April–August) precipitation at Kamloops airport fell by 29% in the first decade of the 2000s compared to the 1990s.

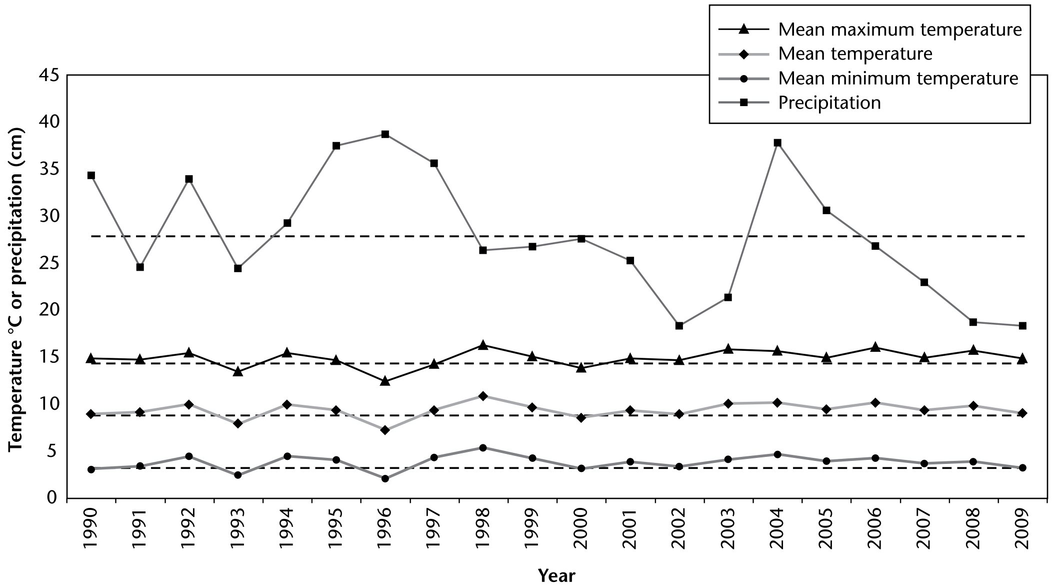

FIGURE 3 *Annual temperature and precipitation for 1990–2009 (solid lines) and annual temperature and precipitation normals for 1971–2009 (dashed lines) from Kamloops Airport (345 m elevation).*

3.5.2 Increased plant competition Although results were mixed and confounded by historical overgrazing, over the past 10–25 years in British Columbia, on some grassland sites subject to grazing, some plant community recovery is taking place (Forest Practices Board 2007). Improved grazing management has the potential to allow residual perennial plants to increase in size and density to the point where they are more competitive against diffuse knapweed (Sheley et al. 1998; Masters and Sheley 2001). A greater cover of perennial grasses and forbs has been attributed to a lower cover of diffuse knapweed (Seastedt et al. 2007; Myers et al. 2009).

Diffuse knapweed frequency was reduced ($P = 0.02$) with increasing frequency of bluebunch wheatgrass on the five sampled sites (Figure 4). In the Bunchgrass and Ponderosa Pine BEC zones of British Columbia, late seral plant communities tend to be more resistant to diffuse knapweed invasion than early seral plant communities (Wikeem et al. 1986). Late seral plant communities within benchmark exclosures from similar grasslands have greater than 25% cover of bluebunch wheatgrass with low contribution from needle-and-thread and big sagebrush (McLean and Marchand 1968). Plant community seral stage was determined for each sampled site by examination of the complete plant community data as well as consideration of exposed mineral soil. Field sampling in 2009 revealed a wide range of plant community stages from early seral through late seral (Table 7). Diffuse knapweed on the five sampled sites tended to be more frequent and have greater percentage cover on the three early seral sites compared to the mid and late seral sites, although one mid-late seral site (Long Lake) did not follow this trend. This trend is consistent with results from an earlier survey of diffuse knapweed occurrence in grassland plant communities in British Columbia (Wikeem et al. 1986); however, neither study provides conclusive evidence for a widespread effect, due to low sample size and an unknown history of diffuse knapweed appearance at the site.

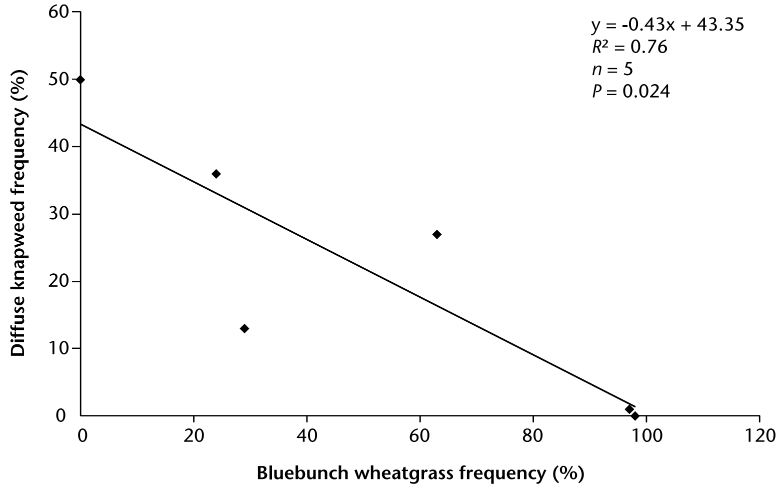

FIGURE 4 *Diffuse knapweed frequency by site, in relation to bluebunch wheatgrass frequency by site, at five diffuse knapweed-invaded sites in southern interior British Columbia.*

TABLE 7 *Cover (%) and frequency (%) of common plant species sampled in 2009 at five diffuse knapweed sites in the southern interior British Columbia*

	Plant species abundance (% cover [% frequency])					
			Prudens			
Common name	**Batchelor**	**Long Lake**	**Grazed**	**Ungrazed**	**Summerland**	**White Lake**
Bluebunch wheatgrass[a]	12 (29)	43 (63)	4 (24)	51 (98)	15 (97)	0 (0)
Sandberg's bluegrass	16 (75)	10 (60)	17 (84)	21 (94)	12 (88)	21 (100)
Needle-and-thread grass	4 (29)	13 (56)	17 (80)	1 (10)	1 (20)	30 (100)
Junegrass	7 (58)	7 (67)	10 (68)	14 (88)	1 (12)	0 (0)
Big sagebrush	7 (25)	0 (0)	3 (16)	0 (0)	25 (50)	0 (0)
Crested wheatgrass	19 (40)	0 (0)	Tr (4)[†]	0 (0)	0 (0)	0 (0)
Yarrow	1 (13)	1 (29)	Tr (8)	12 (84)	Tr (11)	Tr (2)
Thompson's paintbrush	3 (25)	2 (29)	6 (60)	1 (14)	1 (8)	0 (0)
Low pussytoes	3 (40)	1 (13)	6 (56)	1 (10)	Tr (1)	Tr (10)
Umber pussytoes	Tr (4)	2 (23)	1 (16)	1 (28)	0 (0)	3 (24)
Diffuse knapweed	1 (13)	2 (27)	1 (36)	0 (0)	Tr (1)	3 (50)
Cheatgrass	0 (0)	0 (0)	1 (10)	0 (0)	6 (72)	0 (0)
Six-weeks grass	0 (0)	0 (0)	0 (0)	0 (0)	6 (73)	0 (0)
Hillside milk-vetch	1 (4)	3 (29)	0 (0)	1 (4)	0 (0)	0 (0)
Kentucky bluegrass	0 (0)	5 (29)	0 (0)	0 (0)	0 (0)	0 (0)
Corn brome	0 (0)	Tr (4)	0 (0)	0 (0)	4 (51)	0 (0)
Prairie sagewort	1 (10)	Tr (6)	3 (42)	0 (0)	Tr (6)	0 (0)
Exposed mineral soil	34	7	17	5	26	13
Total perennial grass	38	73	48	87	29	51
Seral stage	Early	Mid-late	Early	Late	Mid*	Early

a Scientific names are provided in Appendix 2.
† Tr = < 0.5% cover
* Site is at risk of retrogression to an early seral stage because of the high amount of exposed mineral soil.

3.5.3 Biological control by insects Julien and White (1997) stated that the impact of a biological control agent on its host plant population is predicated on the type of damage that the agents inflict on their host plant as well as by the agent's abundance. This was supported by studies reviewed by Masters and Sheley (2001). The type of damage caused by biological control agents established on diffuse knapweed in British Columbia is well documented in the literature. For example:

- *Agapeta zoegana* was found to be the cause of a significant reduction in spotted knapweed height, above-ground biomass, number of stems, and capitula per bolted plant (Story et al. 2000).
- Corn et al. (2007) found that *Cyphocleonus achates* reduced biomass and caused mortality of mature spotted knapweed plants.
- Myers et al. (2009) found that seed production and density of diffuse knapweed flowering stems were significantly lower due to *Larinus minutus* attack. The combination of *L. minutus* and *Urophora affinis* significantly increased the proportion of seeds destroyed compared to *U. affinis* alone (Crowe and Bourchier 2006).
- The two seed head flies (*U. affinis* and *U. quadrifasciata*) are known to reduce diffuse knapweed seed production by up to 80% (Harris 1980). *U. affinis* can reduce seed production in both attacked and unattacked seed heads by causing a cumulative nutritional drain (Story et al. 1991).

The BCMFR has conducted releases and monitoring of the populations of biological control agents for the past 30 years. The records produced by these efforts can be used to understand the abundance of established knapweed biological control agents across British Columbia (IAPP 2010). In particular, monitoring in proximity to the five sampled sites indicates establishment of multiple agents. Despite the predicted likelihood for high populations of biocontrol agents on the sampled sites, the actual sampled numbers varied widely and were sometimes low (Table 6). Low numbers of sampled insects are likely due to the loss of host plants (Table 3), rather than to poor establishment at the site.

4 CONCLUSIONS

Diffuse knapweed populations and soil seed reserves declined by an average of 74% and 78%, respectively, at five sites in British Columbia from the 1990s to 2009. Most of the literature reports that a decline began in the early 2000s at several locations on western North American rangelands (Seastedt et al. 2003; Myers et al. 2009) which is consistent with this study.

Three factors were discussed as possible causes for the decline of diffuse knapweed at five sites in the southern interior of British Columbia. Climate warming/drying was shown to have occurred over the same period as the reported decline in diffuse knapweed at three Kamloops sites and is a possible contributing factor. Increased plant competition, particularly from bluebunch wheatgrass, may also be a contributing factor; however, the small number of sampling sites in this study cannot provide firm conclusions in this regard. The ubiquitous nature of biological control insects at the five sites, combined with their known abilities to damage knapweed, also places biological control as a possible contributing factor for the decline of diffuse knapweed. It is also possible that two or all of the three factors are acting in concert to reduce diffuse knapweed. For example, climate warming/drying and biological control agents may be acting together synergistically to elevate the rate of decline in knapweed populations on some low-elevation sites. It is known that host plants become more susceptible to injury and mortality by pests when under stressful conditions (Castello et al. 1995; Coakley et al. 1999; Logan et al. 2003; Woods et al. 2005). Determining the cause(s) of the decline in diffuse knapweed plants and soil seed reserves will require a comprehensive study to tease out the type of interaction, if any, among the three factors (additive, synergistic, or antagonistic).

The demonstrated decrease in diffuse knapweed at the five sampled sites provides baseline data that may contribute to a better understanding of how biological control agents, climate warming/drying, and improved grazing management may be interacting on weed-invaded sites in British Columbia.

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APPENDIX 1 Biological control agents introduced to British Columbia from 1970 to 1992 for control of diffuse and spotted knapweed

Biological control agent species	Type	Attack mode	Year introduced	Original target knapweed species	Currently established
Agapeta zoegana	Moth	Root-feeder	1982	Diffuse and spotted	Yes
Chaetorellia acrolophi	Fly	Seed-feeder	1991	Spotted	Yes
Cyphocleonus achates	Weevil	Root-feeder	1987	Spotted	Yes
Larinus minutus	Weevil	Seed-feeder	1991	Diffuse and spotted	Yes
Larinus obtusus	Weevil	Seed-feeder	1992	Diffuse and spotted	Yes
Metzneria paucipunctella	Moth	Seed-feeder	1973	Spotted	Yes
Pelochrista medullana	Moth	Root-feeder	1982	Diffuse	No
Pterolonche inspersa	Moth	Root-feeder	1986	Diffuse	Yes
Sphenoptera jugoslavica	Beetle	Root-feeder	1976	Diffuse	Yes
Subanguina picridus	Nematode	Gall-forming	1985	Diffuse and Russian[1]	No
Terellia virens	Fly	Seed-feeder	1991	Spotted	No
Urophora affinis	Fly	Seed-feeder	1970	Diffuse and spotted	Yes
Urophora quadrifasciata	Fly	Seed-feeder	1972	Diffuse and spotted	Yes
Puccinia jaceae	Fungus	Leaf, stem	Adventive	Diffuse and spotted	Yes
Sclerotinia sclerotiorum	Fungus	Root, leaf, stem	Native	Diffuse and spotted	Yes

1 Russian knapweed (*Acroptilon repens*).

APPENDIX 2 List of plant species at five sites in southern interior British Columbia

Common name	Scientific name	Authority	Origin
Big sagebrush	*Artemisia tridentata*	Nutt.	Native
Bluebunch wheatgrass	*Pseudoroegneria spicata*	(Pursh) A. Löve	Native
Cheatgrass	*Bromus tectorum*	L.	Exotic
Corn brome	*Bromus squarrosus*	L.	Exotic
Crested wheatgrass	*Agropyron cristatum*	(L.) Gaertn.	Exotic
Diffuse knapweed	*Centaurea diffusa*	Lam.	Exotic
Hillside milk-vetch	*Astragalus collinus*	(Hook. ex Hook.) G. Don	Native
Junegrass	*Koeleria macrantha*	(Ledeb.) J.A. Schult. f.	Native
Kentucky bluegrass	*Poa pratensis*	L.	Exotic
Low pussytoes	*Antennaria dimorpha*	(Nutt.) T. & G.	Native
Needle-and-thread grass	*Hesperostipa comata*	(Trin. & Rupr.) Barkw.	Native
Prairie sagewort	*Artemisia frigida*	Willd.	Native
Sandberg's bluegrass	*Poa secunda*	J. Presl	Native
Six-weeks grass	*Vulpia octoflora*	(Walt.) Rydb.	Native
Thompson's paintbrush	*Castilleja thompsonii*	Pennell	Native
Umber pussytoes	*Antennaria umbrinella*	Rydb.	Native
Yarrow	*Achillea millefolium*	L.	Native