Long-term field evaluation of *Mecinus janthinus* releases against Dalmatian toadflax in Montana (USA)

S.E. Sing,[1] D.K. Weaver,[1] R.M. Nowierski[2] and G.P. Markin[3]

Summary

The toadflax stem mining weevil, *Mecinus janthinus* Germar, was first released in the United States in Montana, in 1996. This agent has now become established to varying degrees after subsequent releases made at sites throughout the state. Multiple releases of *M. janthinus* have presented researchers with a unique opportunity to evaluate the efficacy of this agent in diverse habitats and under a variety of environmental conditions. The results presented in this paper summarize findings from long-term field data, illustrating not only the impact of *M. janthinus* on the target weed, Dalmatian toadflax, *Linaria dalmatica* (L.) P. Mill., but also on correlated plant community dynamics. These results additionally provide a valuable means to compare and contrast the biotic response and control efficacy of this agent at both a regional and sub-continental scale.

Keywords: *Linaria*, efficacy, plant community response.

Introduction

Dalmatian toadflax, *Linaria dalmatica* (L.) P. Mill. (Scrophulariaceae) (USDA, NRCS 2007), is an invasive short-lived perennial forb of Mediterranean origin (Alex, 1962). Intentionally introduced to North America as an ornamental plant, *L. dalmatica* is now widespread and has effectively become naturalized through multiple introductions over time (Lajeunesse, 1999). Aspects of the species' life history and morphology, including a root system characterized by a long, well-developed taproot and extensive lateral roots, dual modes of reproduction through seed and vegetative root buds, coupled with a high rate of seed production and long term seed viability undoubtedly contribute to its dominance in disturbed range and forested lands (Robocker, 1974; Vujnovic and Wein, 1997).

Herbicide treatment of Dalmatian toadflax is hampered by two factors: (1) the species' deep root system necessitates precise timing of herbicide application when root carbohydrate reserves are low and the plant is therefore more susceptible to chemical translocation and impact (Robocker *et al.*, 1972) and (2) the protective waxy leaf coating resists herbicide penetration (De Clerck-Floate and Miller, 2001). Chemical control of Dalmatian toadflax is expensive due to the typically large acreages affected. Additionally, repeated herbicide applications are frequently necessary in western US water-limited habitats because each precipitation event has the potential to stimulate Dalmatian toadflax regeneration from fire-resistant rootstocks and characteristically large seedbanks (Zouhar, 2003).

Classical biological control of Dalmatian toadflax in North America was initiated in the late 1960s. To date, eight exotic agent species targeting the flowers, stems, foliage or roots of Dalmatian toadflax have been released or, in the case of adventitiously introduced agents, redistributed, and have established to varying degrees in North America (Smith, 1956; Harris and Carder, 1971; Harris, 1984; De Clerck-Floate and Harris, 2002; McClay and De Clerck-Floate, 2002).

Ten years of research results indicate that biological control of Dalmatian toadflax is feasible, particularly with the stem-boring weevil, *Mecinus janthinus* Germar, the most recently approved agent for control of Dalmatian toadflax. *M. janthinus* has established and

[1] Montana State University, Department of Land Resources and Environmental Sciences, P.O. Box 173120, Bozeman, MT 59717-3120, USA.
[2] USDA-CSREES, 1400 Independence Avenue SW, Stop 2220, Washington, DC 202500-2220, USA.
[3] USDA Forest Service–Rocky Mountain Research Station, 1648 S. 7th Avenue, Bozeman MT 59717, USA.
Corresponding author: S.E Sing <ssing@montana.edu>.

proliferated on many sites throughout western Canada and the United States and is probably the best agent currently available for managing Dalmatian toadflax (Harris *et al.*, 2000; Nowierski, 2004), although population growth is impeded by high levels of overwintering mortality (De Clerck-Floate and Miller, 2002) and site-specific climatic factors (McClay and Hughes, 2007).

Advocates of weed biological control tout this approach for its specificity. Biological control is, in general, a significantly more gradual process than alternative control approaches such as herbicide application. Both of these characteristics facilitate control of the target weed without selectively or intensively influencing immediate changes in the wider vegetation community. Reductions in invasive species such as Dalmatian toadflax should result in the restoration of desirable species, especially those within the target weed's functional group, in the vegetation community. Unfortunately, herbicide treatments frequently result in the desired decrease in Dalmatian toadflax, followed by either an increase in bare ground or replacement with an undesirable species that poses an even greater environmental risk. For instance, cheatgrass (*Bromus tectorum* L.) and exotic, invasive knapweeds commonly invade areas where Dalmatian toadflax has been treated with herbicide; cheatgrass is known to significantly alter vegetation community dynamics and fire cycles (Whisenant, 1990; Billings, 1994), while spotted knapweed (*Centaurea maculosa* Lam.) is regarded as an allelopathic species (Bais *et al.*, 2003). The purpose of this long-term evaluation was to determine if indicators of improved vegetation community dynamics, specifically increased cover of desirable vegetation, can be correlated with the release of the biocontrol agent *M. janthinus*.

Methods and materials

Vegetation data were recorded as early as 4 years before the release of *M. janthinus* (1992) and continued through 2007 at seven release sites located throughout Montana (see Table 1 for site-specific details). The 'Bison Range' site (US Fish and Wildlife Service and Bureau of Indian Affairs) is located in the northwest near Pablo on Flathead Indian Reservation tribal lands adjoining the National Bison Range; three sites, 'Canyon Ferry' (Bureau of Reclamation), 'Elkhorns' (Bureau of Land Management) and 'Mount Helena' (City of Helena Parks and Recreation) are located in the southwest, near the city of Helena, MT; the 'Crow' site (Bureau of Indian Affairs) is located south-centrally on the Crow Reservation, near Lodgegrass, MT; 'Hardy Bridge' (Bureau of Land Management) is located south of Great Falls, MT; and the eastern-most 'Melstone' site (Bureau of Land Management) is located on private ranch land bordering public lands, near the town of the same name.

The initial releases of *M. janthinus* in Montana were made on the Crow and Elkhorns sites in 1996 with limited numbers of adult weevils. *M. janthinus* was first released on the Canyon Ferry and Bison Range sites in 1997, on the Mount Helena site in 1999, and at the Melstone and Hardy Bridge sites in 2000. Permanent, paired 20-m vegetation monitoring transects were initially established to run through the densest local infestations of Dalmatian toadflax at each site. Vegetation data were recorded annually from fixed points at 1-m intervals along each transect. Vegetation attributes were reported from 0.10 m^2 Daubenmire frames placed on fixed sample points, with a total of 40 samples taken annually at each site.

Data collected from each sample frame included counts of Dalmatian toadflax plants and individual stems; the stems were categorized and counted as mature or immature stems. The criterion used to identify mature stems was obvious evidence of flower buds or actual flowering. Stem counts were taken in addition to plant densities because Dalmatian toadflax is not easily or accurately censused on a per-plant basis without destructive excavation. In addition, percent cover of Dalmatian toadflax only and of all forbs other than Dalmatian toadflax was recorded. The remaining area within the sample quadrat not accounted for by one of the vegetation life forms was categorized as non-vegetation cover and included the total area covered by litter, rock and soil. For each plant parameter or vegetation category, mean values for data collected for the year of permanent transect establishment were compared with those for the most recent year of sampling (2006). Mean comparisons were made for each site using a Student's *t* test (Dixon and Massey, 1969).

As part of a non-destructive indicator sampling strategy, 50 randomly selected dead stems from the previous year were collected at each site near, but external to, the monitoring transects. Collecting 'dead' Dalmatian toadflax stems provides a means for evaluating *M. janthinus* establishment and overwintering mortality without influencing weed or insect population trajectories within the monitoring transects. Stems were then split with a scalpel to estimate the number of live or emerged adult weevils. Empty *M. janthinus* chambers are a reliable 1:1 indicator of successful adult *M. janthinus* emergence (R. DeClerck-Floate, personal communication). Weevil mortality was also included as count data and encompassed non-emerged adults, larvae and pupae. Mean comparisons, with $\alpha = 0.05$, were made between emerged adults and dead individuals at each site using a Student's *t* test (Dixon and Massey, 1969).

Results

Overwintering mortality continues to be a concern for Montana *M. janthinus* populations. Estimates of dead

Table 1. Comparison of mean pre- and post-release vegetation attributes (±SE) for transect samples taken at multiple *Mecinus janthinus* release sites.

Site	Year	Transect	No. Dalmatian toadflax stems	Dalmatian toadflax % cover	Other forbs % cover	Bare substrate % cover
Bison Range	1992	1	4.10 ± 0.41	8.80 ± 1.11	5.50 ± 1.05	74.30 ± 2.92
Bison Range	2006	1	0.10 ± 0.07	0.50 ± 0.34	14.00 ± 1.29	72.50 ± 1.83
P values			0.0027	≤0.0001	≤0.0001	0.5596
Bison Range	1992	2	5.00 ± 0.45	15.75 ± 1.71	0.25 ± 0.25	49.75 ± 3.95
Bison Range	2006	2	0.35 ± 0.17	1.00 ± 0.46	9.00 ± 1.39	81.25 ± 1.58
P values			0.0001	≤0.0001	≤0.0001	≤0.0001
Canyon Ferry	1996	1	2.90 ± 0.49	8.30 ± 2.08	6.25 ± 1.73	70.95 ± 3.26
Canyon Ferry	2006	1	6.15 ± 0.88	12.00 ± 1.79	4.25 ± 0.41	70.75 ± 2.21
P values			0.0100	0.2288	0.1654	0.9629
Canyon Ferry	1996	2	5.10 ± 0.69	16.50 ± 2.21	4.25 ± 1.27	61.25 ± 3.70
Canyon Ferry	2006	2	2.45 ± 0.41	4.25 ± 0.83	11.50 ± 2.15	72.75 ± 2.42
P values			0.0164	≤0.0001	≤0.0001	0.0073
Crow	1993	1	5.35 ± 1.09	9.80 ± 2.25	2.75±1.11	65.60 ± 2.83
Crow	2006	1	0.05 ± 0.05	0.25 ± 0.25	7.00 ± 0.76	82.25 ± 1.38
P values			≤0.0001	≤0.0001	0.1071	≤0.0001
Crow	1992	2	7.15 ± 1.25	18.45 ± 2.89	2.05 ± 0.74	61.50 ± 2.70
Crow	2006	2	0.00 ± 0.00	0.00 ± 0.00	9.75 ± 1.12	73.25 ± 1.82
P values			≤0.0001	≤0.0001	0.0113	0.0039
Elkhorns	1992	1	4.40 ± 0.60	12.15 ± 2.21	0.95 ± 0.54	53.55 ± 3.90
Elkhorns	2006	1	0.55 ± 0.20	2.00 ± 0.67	5.75 ± 0.66	72.50 ± 1.68
P values			0.0283	≤0.0001	≤0.0001	≤0.0001
Elkhorns	1992	2	2.80 ± 0.59	10.75 ± 2.30	2.15 ± 0.86	65.00 ± 2.55
Elkhorns	2006	2	1.35 ± 0.44	2.75 ± 0.92	4.25 ± 0.98	76.25 ± 2.20
P values			0.4108	≤0.0001	0.0435	0.0001
Hardy Bridge	2002	1	2.80 ± 0.73	9.50 ± 2.35	3.75 ± 1.02	60.75 ± 2.95
Hardy Bridge	2006	1	0.55 ± 0.28	1.00 ± 0.46	11.50 ± 2.57	64.50 ± 2.56
P alues			0.0123	0.0005	0.0014	0.3363
Hardy Bridge	2002	2	3.10 ± 0.50	12.25 ± 1.56	8.50 ± 1.31	58.50 ± 1.59
Hardy Bridge	2006	2	0.20 ± 0.16	0.50 ± 0.34	4.50 ± 0.88	72.00 ± 1.37
P values			≤0.0001	≤0.0001	0.0028	≤0.0001
Melstone	2000	1	2.30 ± 0.57	11.00 ± 2.39	12.25 ± 1.72	74.00 ± 2.66
Melstone	2006	1	2.00 ± 0.70	5.50 ± 1.95	7.00 ± 0.84	63.50 ± 3.29
P values			0.6923	0.0206	0.0013	0.0145
Melstone	2000	2	2.40 ± 0.39	12.25 ± 2.22	8.50 ± 1.50	73.25 ± 2.67
Melstone	2006	2	2.40 ± 0.54	5.50 ± 1.25	7.75 ± 1.12	74.50 ± 2.35
P values			1.0000	0.0013	0.6038	0.7054
Mount Helena	1992	1	7.60 ± 1.36	14.95 ± 2.09	6.35 ± 1.21	46.70 ± 5.32
Mount Helena	2006	1	2.60 ± 0.63	8.75 ± 1.58	8.75 ± 1.49	68.50 ± 3.12
P values			0.0013	0.0093	0.2483	≤0.0001
Mount Helena	1992	2	9.90 ± 1.23	16.35 ± 1.74	3.70 ± 1.61	43.10 ± 4.03
Mount Helena	2006	2	1.65 ± 0.52	5.00 ± 1.70	10.75 ± 1.42	76.75 ± 2.44
P values			0.0399	≤0.0001	0.0014	≤0.0001

individuals per stem generally outnumbered those of live adults that successfully emerged (Table 2). *M. janthinus* mortality was statistically greater than emergence for at least 1 year of the study at all sites except 'Bison Range' and Hardy Bridge', while mortality was significantly lower than emergence only at 'Bison Range' in 2003. Mortality was as much as fourfold higher than adult emergence at certain sites in some years.

At five of seven study sites, data from both transects showed reductions in toadflax density compared to pre-release levels (Table 1). No significant change was recorded at the Melstone site, while transect 1 at Canyon Ferry showed a significant increase in toadflax density. Percent cover of Dalmatian toadflax was significantly lower at all sites with the exception of transect 1 at Canyon Ferry. We found that percent cover of

Table 2. Estimates of mean (±SE) number of alive and 'dead' *Mecinus janthinus* per *Linaria dalmatica* stem, based on a random sample of 50 stems collected adjacent to release monitoring transects. Alive individuals refer to empty pupal cells, 'dead' individuals refer to the sum of non-emerged adults, pupae and larvae. Means marked with an *asterisk* are significantly different from the other in the same row at $P < 0.05$.

Site	Year	Number of individuals	
		Alive	'Dead'
Bison Range	2003	0.96 ± 0.18*	0.50 ± 0.12
	2004	0.26 ± 0.10	0.28 ± 0.16
	2005	0.00 ± 0.00	0.00 ± 0.00
	2006	0.02 ± 0.02	0.08 ± 0.05
Canyon Ferry	2003	0.08 ± 0.08	0.06 ± 0.03
	2004	0.06 ± 0.04	0.16 ± 0.07
	2005	0.02 ± 0.02	0.12 ± 0.07
	2006	0.04 ± 0.03	0.36 ± 0.11*
Crow	2003	0.66 ± 0.13	1.20 ± 0.18*
	2004	1.68 ± 0.26	2.50 ± 0.44*
	2005	2.08 ± 0.41	3.64 ± 0.52*
	2006	1.80 ± 0.25	1.70 ± 0.26
Elkhorns	2003	0.02 ± 0.02	0.10 ± 0.04*
	2004	0.00 ± 0.00	0.02 ± 0.02
	2005	0.00 ± 0.00	0.00 ± 0.00
	2006	0.20 ± 0.09	0.80 ± 0.25*
Hardy Bridge	2003	0.08 ± 0.03	0.10 ± 0.05
	2004	0.00 ± 0.00	0.02 ± 0.02
	2005	0.00 ± 0.00	0.00 ± 0.00
	2006	0.00 ± 0.00	0.00 ± 0.00
Melstone	2004	1.18 ± 0.25	3.18 ± 0.44*
	2005	0.78 ± 0.14	1.06 ± 0.18
	2006	0.32 ± 0.08	1.44 ± 0.23*
Mount Helena	2003	0.48 ± 0.10	0.78 ± 0.15
	2004	0.88 ± 0.19	2.14 ± 0.47*
	2005	0.94 ± 0.17	1.50 ± 0.25*
	2006	0.70 ± 0.16	2.94 ± 0.40*

forbs other than Dalmatian toadflax increased on 10 of the 14 total transects, and the increase was significant in eight cases. Non-vegetation cover increased significantly on nine transects, remained unchanged on four transects and decreased significantly only on transect 1 at Melstone.

Discussion

The survival of *M. janthinus* was quite low at these sites over the years studied, and this may have reduced potential population growth. It has been reported that extreme temperatures (De Clerck-Floate and Miller, 2002; McClay and Hughes, 2007) and reduced snow cover (De Clerck-Floate and Miller, 2002) reduce survival and population growth of *M. janthinus*. Persistent drought conditions in Montana from 1997 through 2004 undoubtedly affected vegetation dynamics on all sites. The increase in unvegetated area would limit snow retention, which could increase overwintering mortality due to lower temperatures. Although exact environmental conditions have not been determined at these study sites, the locations do experience temperature and precipitation patterns similar to those described for Canada (De Clerck-Floate and Miller 2002), but percent cover of Dalmatian toadflax was lower in Montana, even before biological control was initiated.

However, the general trend towards increased cover of forbs at these sites indicates that climatic conditions alone were not driving the decrease in Dalmatian toadflax density and cover observed at many of our study sites. This may be attributable to biological control altering the overall dynamics of the entire forb community by reducing competition from Dalmatian toadflax. In addition, the increased proportion of forbs that was correlated with an increase in unvegetated area at most sites does suggest that, under comparative environmental extremes, biological control may offer an alternative to protracted non-target impacts from non-selective herbicide.

In addition, we also observed that increased grazing pressure on toadflax appeared to be correlated with drought conditions, especially in late summer when the weed was one of few remaining undesiccated species available. Cattle and wildlife grazing at all sites may have significantly impeded population buildup of *M. janthinus*. Grazing of succulent stems removes developing immature weevils from the population, resulting in a likely reduction in the following season's reproductive population. Weevil populations rebounded when drought conditions eased, and adult weevils became numerous enough to be collected for redistribution on three sites in 2006, suggesting that desiccation before and during winter has also probably been a major impediment to population increase of *M. janthinus* in Montana.

Acknowledgements

This research would not have been possible without the support of the US Forest Service, the Bureau of Land Management, the Bureau of Indian Affairs, US Fish and Wildlife Service, the Bureau of Reclamation and the Crow and the Confederated Kootenai and Salish Indian Tribes. The authors wish to acknowledge with great appreciation Bryan FitzGerald for diligently collecting most of the data associated with this study.

References

Alex, J.F. (1962) The taxonomy, history and distribution of *Linaria dalmatica*. *Canadian Journal of Botany* 40, 295–307.

Bais, H.P., Vepachedu, R., Gilroy, S., Callaway, R.M. and Vivanco, J.M. (2003) Allelopathy and exotic plant invasion: from molecules and genes to species interactions. *Science* 301, 1377–1380.

Billings, W.D. (1994) Ecological impacts of cheatgrass and resultant fire on ecosystems in the western Great Basin. In: Monsen, S.B. and Kitchen, S.G. (eds) *Proceedings, Ecology and Management of Annual Rangelands, May 18–22 1992, Boise ID*, General Technical Report INT-GRT-313, US Department of Agriculture, Forest Service, Ogden UT, USA, pp. 22–30.

De Clerck-Floate, R. and Miller, V. (2001) Biological control of Dalmatian toadflax in British Columbia. Agriculture and Agri-Food Canada, Lethbridge Research Centre, Lethbridge, Canada (pamphlet, 4 pp).

De Clerck-Floate, R.A. and Harris, P. (2002) 72. *Linaria dalmatica* (L.) Miller, Dalmatian toadflax (Scrophulariaceae). In: Mason, P.G. and Huber, J.T. (eds) *Biological Control Programmes in Canada, 1981–2000.* CABI, New York, pp. 368–374.

De Clerck-Floate, R. and Miller, V. (2002) Overwintering mortality of and host attack by the stem-boring weevil, *Mecinus janthinus* Germar, on Dalmatian toadflax (*Linaria dalmatica* (L.) Mill.) in western Canada. *Biological Control* 24, 65–74.

Dixon, W.J. and Massey, Jr., F.J. (1969) *Introduction to Statistical Analysis*, 3rd edn. McGraw Hill, New York, 488 pp.

Harris, P. (1984) *Linaria vulgaris* Miller, yellow toadflax and *L. dalmatica* (L.) Mill., broad-leaved toadflax. In: Kelleher, J.S. and Hulme, M.A. (eds) *Biological Control Programmes Against Insects and Weeds in Canada, 1969–1980*, CAB, Farnham Royal, UK, pp. 179–182.

Harris, P. and Carder, A.C. (1971) *Linaria vulgaris* Miller, yellow toadflax and *L. dalmatica* (L.) Mill., broad-leaved toadflax. In: Kelleher, J.S. and Hulme, M.A. (eds) *Biological Control Programmes Against Insects and Weeds in Canada, 1959–1968*. Commonwealth Institute of Biological Control, Technical Communication No. 4, pp. 94–97.

Harris, P., De Clerck-Floate, R. and McClay, A. (2000) *Mecinus janthinus* Germar. Stem boring weevil. Available at: http://res2.agr.ca/lethbridge/weedbio/agents/amecinus.htm.

Lajeunesse, S.E. (1999) Dalmatian and yellow toadflax. In: Sheley, R.L. and Petroff, J.K. (eds) *Biology and Management of Noxious Rangeland Weeds*. Oregon State University Press, Corvallis, OR, USA, pp. 202–216.

McClay, A.S. and Hughes, R.B. (2007) Temperature and host-plant effects on development and population growth of *Mecinus janthinus* (Coleoptera: Curculionidae), a biological control agent for invasive *Linaria* spp. *Biological Control* 40, 405–410.

McClay, A.S. and De Clerck-Floate, R.A. (2002) *Linaria vulgaris* Miller, yellow toadflax (Scrophulariaceae). In: Mason, P.G. and Huber, J.T. (eds) *Biological Control Programmes in Canada, 1981–2000*. CABI, New York, pp. 375–382.

Nowierski, R.M. (2004) *Mecinus janthinus*. In: Coombs, E.M., Clark, J.K., Piper, G.L. and Confracesco, Jr., A.F. (eds) *Biological control of invasive plants in the United States*. Oregon State University Press, Corvallis, OR, USA, pp. 392–395.

Robocker, W.C. (1974) Life history, ecology, and control of Dalmatian toadflax. *Technical Bulletin 79*. Washington Agricultural Experiment Station, Washington State University, Pullman, WA, USA, 20 pp.

Robocker, W.C., Schirman, R. and Zamora, B.A. (1972) Carbohydrate reserves in roots of Dalmatian toadflax. *Weed Science* 20, 212–214.

Smith, J.M. (1956) Biological control of weeds. In: Vinoth, J. (ed) *1955 Proc. 9th National Weed Committee (Eastern sect.)*. National Weed Committee, Canada Department of Agriculture, Ottawa, ON, Canada, pp. 102–103.

USDA, NRCS. (2007) The PLANTS Database. National Plant Data Center, Baton Rouge, LA, USA. Available at: http://plants.usda.gov (accessed 8 February 2007).

Vujnovic, K. and Wein, R.W. (1997) The biology of Canadian weeds. 106. *Linaria dalmatica* (L.) Mill. *Canadian Journal of Plant Science* 77, 483–491.

Whisenant, S.G. (1990) Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. In: McArthur, E.D., Romney, E.M., Smith, S.D. and P.T. Tueller (compilers) *Proceedings Symposium on Cheatgrass Invasion, Shrub Die-Off and Other Aspects of Shrub Biology and Management*, April 5–7 1989, Las Vegas, NV. Technical Report INT-276, Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, USA, pp. 4–10.

Zouhar, K. (2003) *Linaria* spp. In: *Fire Effects Information System* [Online]. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. Available at: http://www.fs.fed.us/database/feis/plants/forb/linspp (accessed 27 February 2007).