Chapter 12
Biocontrol Arthropods: New Denizens of Canada's Grassland Agroecosystems

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Abstract. Canada's grassland ecosystems have undergone major changes since the arrival of European agriculture, ranging from near-complete replacement of native biodiversity with annual crops to the effects of overgrazing by cattle on remnant native grasslands. The majority of the "agroecosystems" that have replaced the historical native grasslands now encompass completely new associations of plants and arthropods in what is typically a mix of introduced and native species. Some of these species are pests of crops and pastures and were accidentally introduced. Other species are natural enemies of these pests and were deliberately introduced as classical biological control (biocontrol) agents to control these pests. To control weeds, 76 arthropod species have been released against 24 target species in Canada since 1951, all of which also have been released in western Canada. Of these released species, 53 (70%) have become established, with 18 estimated to be reducing target weed populations. The biocontrol programs for leafy spurge in the prairie provinces and knapweeds in British Columbia have been the largest, each responsible for the establishment of 10 new arthropod species on rangelands. This chapter summarizes the ecological highlights of these programs and those for miscellaneous weeds. Compared with weed biocontrol on rangelands, classical biocontrol of arthropod crop pests by using arthropods lags far behind, mostly because of a preference to manage crop pests with chemicals. To date, only one arthropod has been documented as established from the intentional releases of 19 agent species from Eurasia. However, little effort has been devoted to post-release monitoring. Self-dispersal, or accidental introductions, of foreign natural enemies of important arthropod pests has resulted in two species of ladybird beetles and four species of parasitoids becoming established on the Canadian grasslands. For both weed and crop pest biocontrol, there are concerns about the risks of introduced agents to native, non-target species (e.g., the impact of exotic ladybird beetle species), which is driving a call for improved prediction of potential ecological effects prior to agent introductions.

Résumé. Les écosystèmes des prairies canadiennes ont subi beaucoup de changements depuis l'avènement de l'agriculture européenne, du remplacement presque complet de la biodiversité indigène par les cultures annuelles aux effets du surpâturage sur les vestiges des prairies naturelles. La plupart des agroécosystèmes qui ont remplacé les prairies naturelles se composent aujourd'hui d'associations complètement nouvelles de plantes et d'arthropodes constituées typiquement d'un mélange d'espèces introduites et indigènes. Certaines de ces espèces sont des ravageurs des cultures et des pâturages, et ont été introduites accidentellement. D'autres sont des ennemis naturels de ces ravageurs délibérément introduits aux fins de la lutte biologique classique contre ces derniers. Pour lutter contre les mauvaises herbes, 76 espèces d'arthropodes ont été relâchées contre 24 espèces cibles au Canada depuis 1951, et toutes ces espèces ont également été relâchées dans l'ouest du Canada. Cinquante-trois d'entre elles (70 %) se sont établies, et on estime que 18 contribuent effectivement à réduire les populations cibles de mauvaises herbes. Les programmes de lutte biologique contre l'euphorbe ésule dans les provinces des Prairies et contre les centaurées en Colombie-Britannique — les deux plus importants jamais mis en œuvre au Canada — ont chacun mené à l'établissement de 10 nouvelles espèces d'arthropodes sur les parcours naturels. Le présent chapitre résume les faits saillants écologiques de ces programmes et de ceux visant diverses autres espèces de mauvaises herbes. Comparativement à la lutte biologique contre les mauvaises herbes dans les parcours naturels,

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les programmes de lutte biologique classique contre les ravageurs des cultures sont très peu avancés, ce qui s'explique principalement par la préférence accordée dans ce domaine à la lutte chimique. Jusqu'à maintenant, les lâchers délibérés de 19 agents biologiques eurasiens n'ont donné lieu à l'établissement confirmé que d'une seule espèce d'arthropode. Toutefois, on a consacré peu d'efforts au suivi des résultats des lâchers. L'auto-dispersion ou l'introduction accidentelle d'ennemis naturels étrangers d'arthropodes nuisibles importants ont conduit à l'établissement de deux espèces de coccinelles et de quatre espèces de parasitoïdes dans les prairies canadiennes. Les risques que posent pour les espèces indigènes non ciblées les espèces introduites pour la lutte biologique contre les mauvaises herbes et les ravageurs (par exemple, les incidences des coccinelles exotiques) suscitent des préoccupations et justifient les appels en faveur d'une amélioration des méthodes de prévision des effets écologiques possibles de l'introduction de ces agents biologiques.

Introduction

The native grassland ecosystems of western Canada have experienced major environmental shifts since the arrival of European settlers in the late 1800s (see Chapter 1) and now mostly exist as human-altered ecosystems ("agroecosystems") with simplified ecological communities. Former expansive fields of native biological diversity were plowed and sown to crops or overgrazed by cattle prior to the 1930s, and an assessment to the 1990s estimates a total loss of 70% of our native prairie grasslands and 19% of bunchgrass/sagebrush habitat in British Columbia (Federal, Provincial and Territorial Governments of Canada 2010). Today, only fragmented remnants of our original prairie grasslands exist, and the remnant natural grasslands of the British Columbia interior continue to be threatened by human activities (Gayton 2004; Scudder 2010).

Thus, once pristine and speciose native grasslands now comprise new associations of plants and arthropods spanning a continuum of introduced and native species. At one extreme are rangelands, which include grazeable forest lands, shrub lands, tame pastures, riparian areas, and natural grasslands (Adams *et al.* 2009). When properly managed, grazing by cattle on natural grasslands optimizes ecosystem function and the diversity of native plant and animal species. Overgrazing can degrade and destabilize the grassland ecosystem, as indicated by a loss of structural heterogeneity and species diversity and by an increase in the incidence of invasive plants, that is, "weeds" (Adams *et al.* 2009; see Chapter 1). The introduction of weedy species, in turn, has implications for resident species of native arthropods. Weeds, particularly those of Eurasian origin, can invade even healthy, intact grasslands, aided by adjacent disturbed sites and by fragmentation due to resource extraction (e.g., oil wells) and roads. Currently, large tracts of natural grasslands are dominated by introduced weeds in Canada, at great cost both economically and environmentally (Colautti *et al.* 2006). At the other extreme of the continuum are the annual crop systems that are made up of monocultures of non-native or genetically altered plants, together with a few introduced or native pest arthropods and weeds. Native pollinator insects or natural enemies of the pests may be present but can have difficulty surviving the repeated, severe disturbances (i.e., tillage, harvest, pesticide applications) characteristic of these production systems.

The release of arthropods as biocontrol agents for target pest species provides an option in addition to the current reliance on chemical and cultural methods of control (Mason and Huber 2002; Boyetchko *et al.* 2009). These arthropods are typically host-specific natural enemies (i.e., parasitoids, predators, or herbivores) of targeted non-native pests from their place of origin. They are first selected as candidates for biocontrol on the basis of published overseas host records (i.e., what they were found feeding on or associated with in the field), or during dedicated overseas surveys of target pests. The most promising of these arthropods then are used in host-specificity tests to determine what they are capable of feeding on, and only the most host-specific of these are considered for release, thereby keeping potential agricultural/horticultural or environmental risks to a minimum (De Clerck-Floate *et al.* 2006). The tests are conducted in laboratory or field conditions overseas, or within quarantine laboratories in the place of proposed introduction, and can take many years to complete (e.g., 10 years plus for some weed biocontrol agents). They typically comprise investigations of the feeding or egg-laying preferences of adults when presented with a selected range of potential host species, and importantly, of the ability of tested species to complete full development, from egg to adult, on potential hosts (De Clerck-Floate *et al.* 2006). Once the host-specificity screening is completed, the data are combined with all known scientific information on each candidate agent into a petition for release, which is submitted to our regulatory agency (Canadian Food Inspection Agency; CFIA) for expert review. The science-based decision to release biocontrol arthropods in Canada is the responsibility of CFIA under the *Plant Protection Act*, but also involves input from the USA and Mexico following standards of the North American Plant Protection Organization (De Clerck-Floate *et al.* 2006). Although agents for both biocontrol of weeds and arthropod pests currently undergo host-specificity screening, testing continues to be more extensive and advanced for the former, because it is easier to identify, obtain, and manipulate plants than potential arthropod hosts for the testing of candidate agents.

Once a petitioned foreign arthropod has been given regulatory approval for release, it is then introduced into its new environment in small numbers, a practice termed "classical biological control" (Van Driesche and Bellows 1996). A variant of this, "neoclassical biological control," introduces non-native arthropods that attack a foreign plant or insect species to target a native pest species that is closely related to the foreign host (Lockwood 1993). In Canada, classical biocontrol is used in the control of plant and arthropod pests, whereas neoclassical biocontrol is used only in arthropod pest control. Ultimately, the aim of both classical and neoclassical biocontrol is to use natural, specialized predator–prey interactions to reduce pest populations below economic or environmentally damaging thresholds while establishing self-sustaining and dispersing populations of the introduced biocontrol agent. The pest is not eradicated, such that low levels of the biocontrol agent remain to prevent further pest outbreaks. The successful biocontrol agents thus become part of the extant arthropod communities of our agroecosystems.

In this chapter, we review the use of arthropod agents to control key pests on native rangelands and in agricultural crops of western Canada. On rangelands, the key pests are weeds and thus the biocontrol agents are herbivorous insects. In crops, weeds are most easily controlled with herbicides and therefore the agents are parasitoids and predators of pest insects. We focus on arthropod species that have become established since their release and, to a lesser extent, on species whose establishment success has not been determined. We exclude arthropod species released to control pests of forests and orchards, given the focus of this volume on grassland habitats.

Arthropod Introductions for Weed Biocontrol

Classical biocontrol of weed species through the introduction of their natural enemies is a key strategy, if not the only long-term strategy, to mitigate and manage the impacts of these plants in natural habitats (Hoddle 2004). It is often the only option when weed infestations are too extensive, too difficult to access, and/or too costly to manage by using chemicals or mechanical means of control. It is also an important option when herbicide use is restricted, for example, near natural bodies of water or in habitats harbouring species at risk. Classical weed biocontrol tends to work best in habitats that are relatively undisturbed (e.g., grasslands), which allows the intended interaction between target host plant and arthropod populations to run its course unabated. The method is rarely used in annual crops where weeds are more easily controlled with cultivation and herbicides. Its use in perennial crops, which have a disturbance level intermediate between that of grasslands and annual crops, has yet to be fully explored.

In Canada, classical biocontrol of weeds has been practiced for 60 years with numerous successes, especially on western rangelands. The program began in 1951–1952 with the release of the leaf beetle species, *Chrysolina quadrigemina* (Suffrain) and *C. hyperici* (Forster) (Coleoptera: Chrysomelidae) to successfully control the rangeland weed, St. John's wort (*Hypericum perforatum* L.; Clusiaceae) in British Columbia (Table 1). In total, 76 arthropod species have been introduced against 24 weed species in Canada, with all of these also released in our western provinces. The establishment rate for these 76 arthropod species is 70%, which is higher than that typically reported for establishment of classical weed biocontrol agents released elsewhere in the world (e.g., 60%; McFayden 1998). However, not all of these established species are widespread on their respective hosts, nor have they all been deemed successful (i.e., either completely or substantially reducing weed populations to below economically or environmentally damaging levels; McFayden 1998). Harris (1991) estimated that of those weed biocontrol agents that have established in Canada, one-third had some level of control on the targeted plant species. A quick reassessment based on the current tally of 53 established species (Tables 1–4) reveals that approximately 18 (i.e., 34%) are reported as having detectable impact on host weed populations; this information is provided from personal field experience (RD-F) and recent reports (e.g., Mason and Huber 2002). Notable recent successes include (a) the control of leafy spurge, *Euphorbia esula* (L.) (Euphorbiaceae), in dry grassland habitats of western Canada following release of root-feeding flea beetle species in the genus *Aphthona* (Coleoptera: Chrysomelidae) (Table 2 and see Bourchier *et al.* 2002*b*); (b) reductions of diffuse knapweed, *Centaurea diffusa* Lam. (Asteraceae), in British Columbia following release of the seed weevil, *Larinus minutus* Gyllenhal (Coleoptera: Curculionidae) (Table 3, and see Myers *et al.* 2009); (c) the control of Dalmatian toadflax, *Linaria dalmatica* (L.) Mill. (Plantaginaceae), on native rangelands in British Columbia following release of the stem-boring weevil, *Mecinus janthinus* Germar (Coleoptera: Curculionidae) (Fig. 1, Table 1; and see Van Hezewijk *et al.* 2010); and (d) the amazingly rapid success of the root weevil, *Mogulones crucifer* (Pallas) (Coleoptera: Curculionidae), in controlling populations of houndstongue, *Cynoglossum officinale* L. (Boraginaceae), in British Columbia and Alberta (Fig. 2, Table 1; and see De Clerck-Floate and Wikeem 2009). In these examples, the introduced insects have reduced, but have not eliminated, the target weed. Thus, populations of the insects remain at low, sustainable levels in the environment, as expected for classical weed biocontrol.

One cannot describe biocontrol of weeds in Canada's altered grassland habitats without specific mention of programs for the biocontrol of leafy spurge (Fig. 3A) in the prairie provinces and for diffuse and spotted knapweed, *Centaurea stoebe* L. ssp. *micranthos* (Gugler) Hayek (Asteraceae) (Fig. 4A), in British Columbia. These invasive plant species arrived adventively (i.e., on their own) from Eurasian grassland habitats during European settlement of the Canadian west in the 1800s and quickly spread in the absence of their natural enemies. By the mid-1990s, leafy spurge was estimated to infest over 150,000 ha in Alberta, Saskatchewan, and Manitoba (Bourchier *et al.* 2002*a*). By the late 1970s, the

Table 1. Arthropods released and established in western Canada to control weeds. The year of first reported release is provided for the indicated province, with establishment documented for provinces in bold font, as supported by the superscript reference(s).

ORDER (Common Name) **Family** **Genus species**	**Feeding Guild**	**Weed(s) Released against**	**Year of 1st Release**
ACARINA (Mites)			
Eriophyes			
Aceria malherbae Nuzzaci	Leaf and bud galler	Field bindweed (*Convolvulus arvensis* L.)	1989 (SK); 1992 (BC, MB); 1993 (**AB**[1])
COLEOPTERA (Beetles)			
Buprestidae			
Agrilus hyperici (Creutzer)	Root miner	St. John's wort (*Hypericum perforatum* L.)	1955 (**BC**[2])
Chrysomelidae			
Cassida azurea Fabricius	Defoliator	Bladder campion (*Silene vulgaris* (Moench) Garcke)	1989 (**MB**, **SK**)[6]; 1990 (**AB**[6])
Chrysolina hyperici (Forster)	Defoliator	St. John's wort	1951 (**BC**[2]); 1990 (MB[?, 3])
Chrysolina quadrigemina (Suffrain)	Defoliator	St. John's wort	1952 (**BC**[2,3])
Galerucella calmariensis (L.)	Defoliator	Purple loosestrife (*Lythrum salicaria* L.)	1992 (**MB**[8]); 1993 (**AB**, **BC**)[8]; 1999 (**SK**[8])
Galerucella pusilla (Duftschmid)	Defoliator	Purple loosestrife	1992 (**MB**[8]); 1993 (**AB**, **BC**)[8]; 1999 (**SK**[8])
Longitarsus flavicornis (Stephens)	Root miner	Tansy ragwort (*Jacobaea vulgaris* P. Gaertn)	1971 (**BC**[2])
Longitarsus jacobaeae (Waterhouse)	Root miner	Tansy ragwort	1971 (**BC**[2])
Longitarsus quadriguttatus (Pontoppidan)	Root miner	Houndstongue (*Cynoglossum officinale* L.)	1998 (**BC**[2,9]); 1999 (**AB**[9])

Table 1. (continued)

ORDER (Common Name) Family Genus species	Feeding Guild	Weed(s) Released against	Year of 1st Release
COLEOPTERA (Beetles) ***continued***			
Curculionidae			
Hylobius transversovittatus Goeze	Root miner	Purple loosestrife	1992 (**MB**[8]); 1994 (**AB**[8], BC)
Mecinus janthinus Germar	Stem miner	Dalmatian toadflax (*Linaria dalmatica* (L.) Mill.)	1991 (**BC**[2,4]); 1992 (**AB**[4])
		Yellow toadflax (*Linaria vulgaris* Mill.)	1994 (**AB**[5]); 1996 (SK); **BC***
Microplontus edentulus (Schultze)	Stem miner	Scentless chamomile (*Tripleurospermum perforatum* (Mérat) M. Lainz)	1997 (**AB**[10], BC); 1998 (MB, SK)
Mogulones crucifer (Pallas)	Root miner	Houndstongue	1997 (**BC**[2,9]); 1998 (**AB**[9])
Nanophyes marmoratus Goeze	Flower feeder	Purple loosestrife	1994 (AB, BC); 1997 (**MB**[8])
Omphalapion hookeri (Kirby)	Seed feeder	Scentless chamomile	1992 (**AB**, **BC**, **MB**, **SK**)[10]
Rhinusa antirrhini (Paykull)	Seed feeder	Dalmatian toadflax	1993 (**BC**[2,4]); 1994 (AB)
Rhinusa linariae (Panzer)	Root galler	Yellow toadflax	1997 (AB, **BC**[2,5])
DIPTERA (Flies)			
Anthomyiidae			
Botanophila seneciella (Meade)	Receptacle and seed feeder	Tansy ragwort	1968 (**BC**[2])

Cecidomyiidae			
Cystiphora sonchi (Bremi)	Leaf galler	Perennial sowthistle (*Sonchus arvensis* L.)	1981 (**AB**, **SK**)[7]; 1982 (**MB**[7]); 1984 (BC)
Rhopalomyia tripleurospermi Skuhrava	Bud galler	Scentless chamomile	1999 (**AB**[11], **BC**[2,11], MB[?,11] **SK**[11])
HEMIPTERA (True Bugs)			
Aphididae			
Aphis chloris (Koch)	Stem and crown sucker	St. John's wort	1979 (**BC**[2,3]); 1990 (MB)
LEPIDOPTERA (Butterflies, Moths)			
Geometridae			
Aplocera plagiata (L.)	Defoliator	St. John's wort	1976 (**BC**[2,3]); 1981 (SK)
Noctuidae			
Calophasia lunula (Huffnagel)	Defoliator	Dalmatian toadflax	1963 (**BC**[2,4]); 1991 (AB)
		Yellow toadflax	1965 (SK);1985 (AB); **BC***
Tyria jacobaeae (L.)	Defoliator	Tansy ragwort	1962 (**BC**[2])
Tortricidae			
Cochylis atricapitana (Stephens)	Stem and crown miner	Tansy ragwort	1990 (**BC**[2])

[1] McClay and De Clerck-Floate (2002*a*); [2] Biocontrol Agents and Host Plants in BC (http://www.for.gov.bc.ca/hra/plants/biocontrol/bcmatrix.htm); [3] Jensen *et al.* (2002); [4] De Clerck-Floate and Harris (2002); [5] McClay and De Clerck-Floate (2002*b*); [6] Peschken *et al.* (2002); [7] McClay and Peschken (2002); [8] Lindgren *et al.* (2002); [9] De Clerck-Floate and Schwarzländer (2002); [10] McClay *et al.* (2002*b*); [11] Alec McClay, McClay Ecoscience, Sherwood Park, AB, pers. comm.

*Moved on own from Dalmatian toadflax to yellow toadflax (RD-F, pers. obs, 2004-2010); AB = Alberta, BC = British Columbia, MB = Manitoba, SK = Saskatchewan; [?] = not detected despite monitoring as indicated by accompanying reference(s).

Table 2. Foreign biocontrol arthropods released and established on leafy spurge, *Euphorbia esula* L., in western Canada. The year of first reported release is provided for the indicated province, with establishment documented for provinces in bold font, as supported by the superscript reference(s).

ORDER (Common Name) Family Genus species	Feeding Guild	Year of 1st Release
COLEOPTERA (Beetles)		
Chrysomelidae		
Aphthona cyparissiae (Koch)	Root miner	1982 (**AB**, **MB, SK**)[1]; 1989 (**BC***[,1,2] – mixed with *A. nigriscutis*)
Aphthona czwalinae Weise	Root miner	1985 (**AB**[1], SK); 1986 (**MB**[1]); 1995 (**BC***[,2] – mixed with *A. lacertosa*)
Aphthona flava Guillebaume	Root miner	1982 (**AB**[1]); 1983 (SK); 1990 (**BC**[1,2])
Aphthona lacertosa Rosenhauer	Root miner	1987 (**SK**[1]); 1990 (**AB**[1]); 1991 (**MB**[1]); 1995 (**BC***[,1,2])
Aphthona nigriscutis Foudras	Root miner	1983 (**MB**, **SK**)[1]; 1986 (**AB**[1]); 1989 (**BC***[,1,2])
Cerambycidae		
Oberea erythrocephala (Schrank)	Stem and root miner	1979 (SK); 1980 (**AB**[1]); 1981 (MB)
DIPTERA (Flies)		
Cecidomyiidae		
Spurgia capitigena (Bremi)	Shoot tip galler	1987 (**AB**[1], MB, **SK**[1])
Spurgia esulae (Gagne)	Shoot tip galler	1987 (**AB**, **MB**, **SK**)[1]; 1990 (BC[?,2])
LEPIDOPTERA (Butterflies, Moths)		
Sphingidae		
Hyles euphorbiae (L.)	Defoliator	1966 (BC[?,2], MB, SK); no releases (**AB**[1])
Tortricidae		
Lobesia euphorbiana (Freyer)	Defoliator/ leaf tier	1987 (**MB**[1]); 1990 (AB, **BC**[1,2]); 1991 (**SK**[1])

[1] Bourchier *et al.* (2002*a*); [2] Biocontrol Agents and Host Plants in BC (http://www.for.gov.bc.ca/hra/plants/biocontrol/bcmatrix.htm).

AB = Alberta, BC = British Columbia, MB = Manitoba, SK = Saskatchewan; * = assumed species established, but needs verification; ? = not detected despite monitoring as indicated by accompanying reference(s).

Fig. 1. Dalmatian toadflax (*Linaria dalmatica*) (A), which invades dry, coarse-soil rangeland slopes, is currently being controlled in regions of southern British Columbia by the introduced stem-boring weevil, *Mecinus janthinus* (B). Photos by R. De Clerck-Floate, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

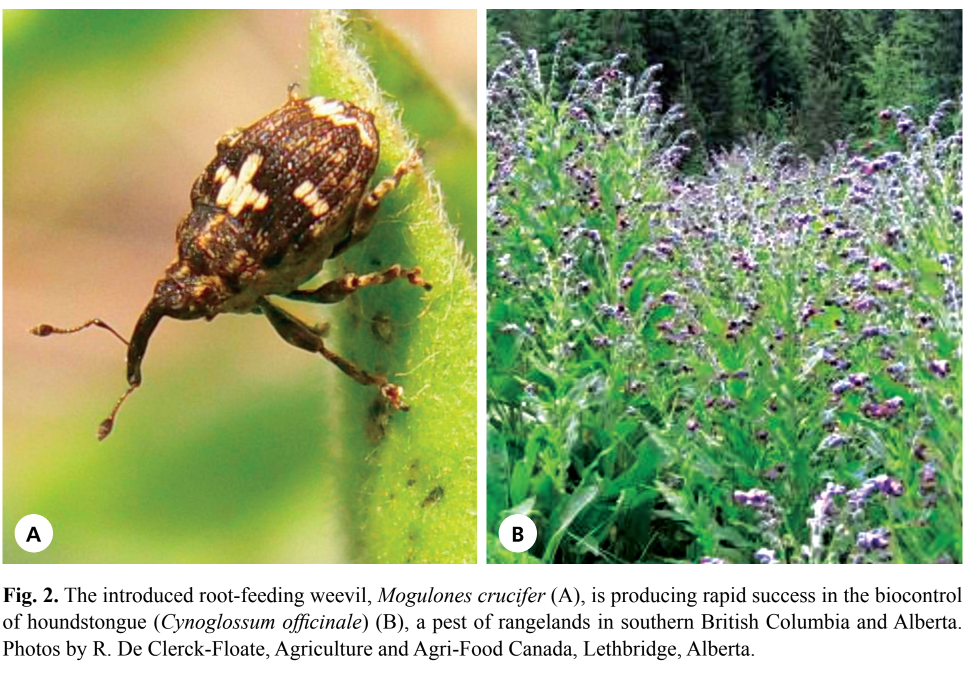

Fig. 2. The introduced root-feeding weevil, *Mogulones crucifer* (A), is producing rapid success in the biocontrol of houndstongue (*Cynoglossum officinale*) (B), a pest of rangelands in southern British Columbia and Alberta. Photos by R. De Clerck-Floate, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

knapweeds were estimated to infest 1.1 million ha of native grassland in British Columbia alone (Harris and Cranston 1979). Infestations reduced land values and productivity, which led ranchers and land managers in affected areas to consider biocontrol as a cost-effective solution. Between 1965 and 1994, 18 arthropod species were released in western Canada for the control of leafy spurge and also for cypress spurge (*Euphorbia cyparissias* L.) (Euphorbiaceae). Ten of these agents became established: five species of *Aphthona* flea beetles, two species of defoliating moth (Lepidoptera: Sphingidae, Tortricidae), a stem/root mining beetle (Coleoptera: Cerambycidae), and two gall fly species (Diptera: Cecidomyiidae) (Table 2). The program for diffuse and spotted knapweed in British Columbia began in Canada in 1970 with the release of the seed-galling fly, *Urophora affinis* Frauenfeld (Diptera: Tephritidae). By 1991, 12 arthropod agents had been screened and released in western Canada (particularly in British Columbia), with 10 successfully becoming established (Table 3).

Many of the established agents for the spurge and knapweed programs are now widespread due to both human facilitated movement and natural dispersal. Species of *Urophora* seed-galling flies on knapweeds are highly mobile and readily find new host plant infestations. Thus, *Urophora quadrifasciata* (Meigen) (Diptera: Tephritidae) is well-established in Alberta on both diffuse and spotted knapweed, although it was never recorded as released in this province (Table 3). In contrast, the *Aphthona* beetles on spurge and the root-mining weevil, *Cyphocleonus achates* (Fahraeus) (Coleoptera: Curculionidae), on knapweeds (Fig. 4B) are relatively slow to disperse, despite being able to build to high numbers locally several years after release. Thus, these latter insects were part of extensive and successful provincial collection and redistribution programs in the 1990s (Bourchier *et al.* 2002*a*, 2002*b*). However, the root-mining moth, *Pterolonche inspersa* Staudinger (Lepidoptera: Pterolonchidae), which was released against diffuse and spotted knapweed in British Columbia in 1986 (Table 3), was so slow to build in number and disperse that it was not until 2000 that establishment was confirmed (Bourchier *et al.* 2002*b*).

The spurge and knapweed programs also illustrate how knowledge of habitat preferences or of interspecies interactions of the agents may facilitate weed management. For control of

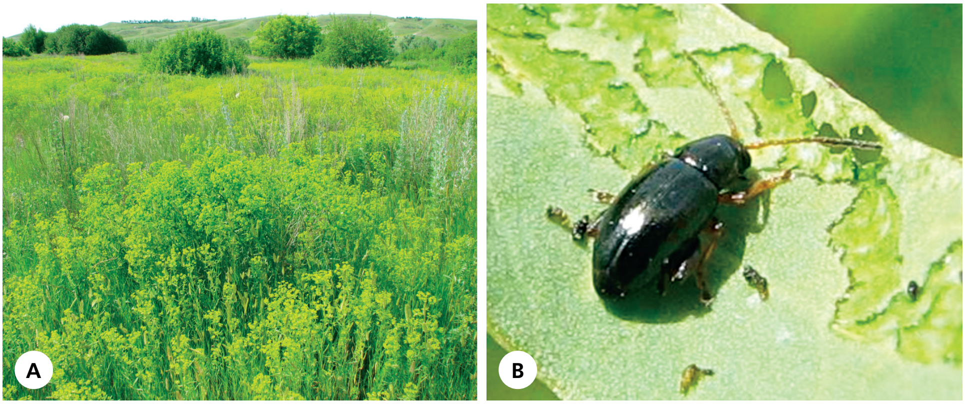

Fig. 3. The invasive Eurasian weed, leafy spurge (*Euphorbia esula*), infests over 150,000 ha of native prairie in Alberta, Saskatchewan, and Manitoba (A). *Aphthona lacertosa* Rosenhauer (Coleoptera: Chrysomelidae) (B) is one of several species of root-feeding beetles within the same genus that have been introduced to Canada from Eurasia to help control leafy spurge. Photos by B. Van Hezewijk, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

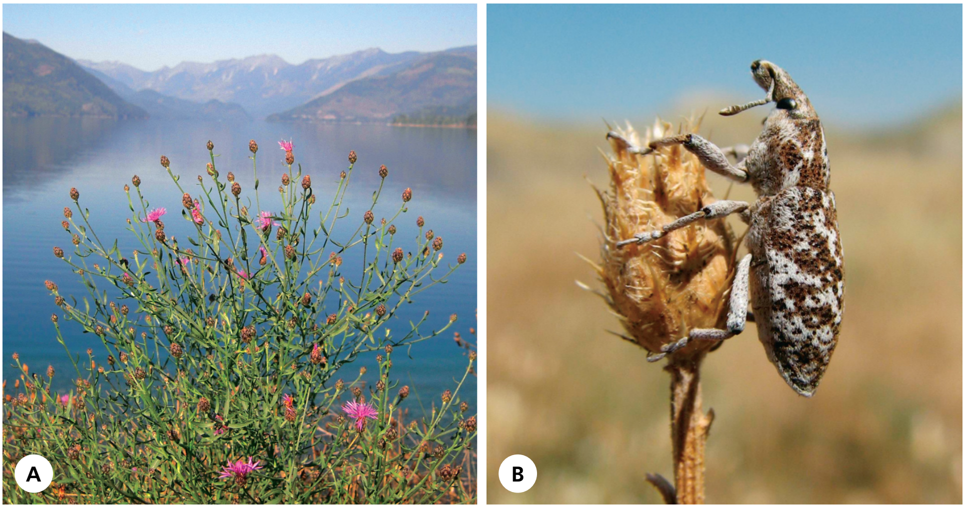

Fig. 4. Spotted knapweed (*Centaurea stoebe* L. ssp. *Micranthos)* is a major invasive weed on native rangelands in British Columbia (A). The root-feeding weevil, *Cyphocleonus achates* (B), is one of 10 successfully established biocontrol insects introduced against knapweeds in Canada. The large, docile adults emerge in late summer/ early fall and can be readily seen clinging to the tops of their host weeds. Knapweed photo by V. Miller, British Columbia Ministry of Natural Resource Operations, Nelson, British Columbia and weevil photo by B. van Hezewijk, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

spurge, the flea beetle *Aphthona nigriscutis* Foudras (Coleoptera: Chrysomelidae) is most successful in open, warm, dry prairie habitats with coarse/sandy soils. In contrast, *Aphthona lacertosa* Rosenhauer (Coleoptera: Chrysomelidae) (Fig. 3B) does better on loamy soils and dry to wet habitats (Bourchier *et al.* 2002*a*). Similarly, attention needs to be given to potential competitive interactions among different agents that share the same plant resource. When they co-occur on spotted knapweed (*Centaurea stoebe* L.ssp. *micranthos* (Gugler) Hayek), the seed-galling fly, *U. affinis*, may outcompete the seed weevil, *L. minutus*, to reduce the overall level and efficacy of biocontrol (Crowe and Bourchier 2006).

Similar lessons are illustrated by research on the biocontrol of introduced species of thistles in the genera *Cirsium, Carduus,* and *Onopordum* (Asteraceae) (Table 4). These prickly colonists of rights-of-way, crops, and pastures arrived during European settlement and have been difficult to control ever since. Canada thistle (*Cirsium arvense* (L.) Scop.) is a particularly serious and widespread weed of crops and pastures (McClay *et al.* 2002*a*) and is also a moderately invasive species of disturbed natural areas (White *et al.* 1993). Seven of the eight arthropod agents introduced to control thistles have successfully established in western Canada and comprise species of Chrysomelidae (one species), Curculionidae (three species), and Tephritidae (three species) (Table 4). Only the leaf-feeding beetle, *Altica carduorum* Guérin-Méneville (Coleoptera: Chrysomelidae), first introduced in 1969 against Canada thistle, has failed to become established (McClay *et al.* 2002*a*). These agents attack various parts of their targeted hosts, including buds, flower and seed heads, stems, root crown, and leaves (Table 4), but overall, have not been effective in control. The sole exception has been the flower receptacle-mining/galling weevil, *Rhinocyllus conicus* (Frölich) (Coleoptera: Curculionidae). First released in 1968 on nodding plumeless thistle (*Carduus nutans* L.) in Saskatchewan and spiny plumeless thistle (*Carduus acanthoides* L.) in British Columbia

Table 3. Foreign biocontrol arthropods released and established on diffuse knapweed (*Centaurea diffusa* Lam.), meadow knapweed (*C. x moncktonii* C.E. Britton), and/or spotted knapweed (*C. stoebe* L. ssp. *micranthos* (Gugler) Hayek) in western Canada. The year of first reported release is provided for the indicated province, with establishment documented for provinces in bold font, as supported by the superscript reference(s).

ORDER (Common Name) Family Genus species	Feeding Guild	Weed(s) Released against	Year of 1st Release
COLEOPTERA (Beetles)			
Buprestidae			
Sphenoptera jugoslavica Obenberger	Root galler	Diffuse knapweed	1976 (**BC**[1,3])
		Spotted knapweed	1987 (**BC**[1,3])
Curculionidae			
Cyphocleonus achates (Fahraeus)	Root miner	Diffuse knapweed	1987 (**BC**[1,3]); 2000 (**AB**[2])
		Spotted knapweed	1987 (**BC**[1,3]); 1996 and 2000 (AB[?,2])
Larinus minutus Gyllenhal	Seed feeder	Diffuse knapweed	1991 (**BC**[1,3])
		Spotted knapweed	1991 (**BC**[1,3])
Larinus obtusus Gyllenhal	Seed feeder	Spotted knapweed	1992 (**BC**[1,3])
DIPTERA (Flies)			
Tephritidae			
Urophora affinis (Frauenfeld)	Receptacle galler	Diffuse knapweed	1970 (**BC**[1,3]); **AB***[,1]
		Spotted knapweed	1970 (**BC**[1,3]); 1976 (**AB**[2])

Urophora quadrifasciata (Meigen)	Ovary galler	Diffuse knapweed	1972 (**BC**[1,3]); **AB***[,2]
		Spotted knapweed	1972 (**BC**[1,3]); **AB***[,2]
		Meadow knapweed	1987 (**BC**[3])
LEPIDOPTERA (Butterflies, Moths)			
Gelechiidae			
Metzneria paucipunctella Zeller	Receptacle and seed miner	Diffuse knapweed	1981 (**BC**[1]); 1985 (AB[?,2])
		Spotted knapweed	1973 (**BC**[1,3])
Pterolonchidae			
Pterolonche inspersa Staudinger	Root miner	Diffuse knapweed	1986 (**BC**[1,3])
		Spotted knapweed	1991 (**BC**[1,3])
Tortricidae			
Agapeta zoegana L.	Root miner	Diffuse knapweed	1982 (**BC**[1,3])
		Spotted knapweed	1982 (**BC**[1,3]); 1989 (**AB**[1])
Pelochrista medullana Staudinger	Root miner	Diffuse knapweed	1982 (BC[?,1,3])
		Spotted knapweed	1982 (BC[?,1,3])

[1] Bourchier *et al.* (2002*b*); [2] Brian Van Hezewijk, AAFC, Lethbridge Research Centre, Lethbridge, AB, pers. comm.; [3] Biocontrol Agents and Host Plants in BC (http://www.for.gov.bc.ca/hra/plants/biocontrol/bcmatrix.htm).

AB = Alberta, BC = British Columbia; [?] = not detected despite monitoring as indicated by accompanying reference(s); * = no record of release and so presumed adventive.

Table 4. Foreign biocontrol arthropods released and established on spiny plumeless thistle (*Carduus acanthoides* L.), Canada thistle (*Cirsium arvense* (L.) Scop.), nodding plumeless thistle (*Carduus nutans* L.), marsh thistle (*Cirsium palustre* (L.) Scop.), and/or bull thistle (*Cirsium vulgare* (Savi) Ten.) in western Canada. The year of first reported release is provided for the indicated province, with establishment documented for provinces in bold font, as supported by the superscript reference(s).

ORDER (Common Name) Family Genus species	Feeding Guild	Weed(s) Released Against	Year of 1st Release
COLEOPTERA (Beetles)			
Curculionidae			
Hadroplontus litura (Fabricius)	Stem and crown miner	Canada thistle	1983 (AB[?,1]); 1985 (**SK**[1]); 1987 (BC[?,2]); 1989 (MB)
Lema cyanella (L.)	Defoliator	Canada thistle	1982 (SK); 1993 (**AB**[1])
Rhinocyllus conicus (Frölich)*	Receptacle miner/galler	Marsh thistle	1997 (**BC**[2])
		Nodding plumeless thistle	1968 (**SK**[3]); 1974 (**MB**[3]); 1979 (**BC**[2,3]);1988 (**AB**[3])
		Spiny plumeless thistle	1968 (**BC**[2])
Trichosirocalus horridus (Panzer)	Bud miner	Nodding plumeless thistle	1975 (**SK**[3]); 1979 (**BC**[2,3]); 1980 (**MB**[3]); 1988 (**AB**[3])
		Spiny plumeless thistle	1975 (**BC**[2,3])
DIPTERA (Flies)			
Tephritidae			
Urophora cardui (L.)	Stem galler	Canada thistle	1984 (**SK**[1]); 1987 (**BC**[1,2]); 1996 (**AB**[1])
Urophora solstitialis (L.)	Receptacle galler	Nodding plumeless thistle	1991 (BC[?,2], **SK**[3])
		Spiny plumeless thistle	1990 (BC[?, 2,3], SK)
Urophora stylata (L.)	Receptacle galler	Bull thistle	1973 (**BC**[2])

[1] McClay et al. (2002a); [2] Biocontrol Agents and Host Plants in BC (http://www.for.gov.bc.ca/hra/plants/biocontrol/bcmatrix.htm); [3] Julien and Griffiths (1998).

*Also has moved onto introduced and native *Cirsium* spp. in western Canada[1,2]

AB = Alberta, BC = British Columbia, MB = Manitoba, SK = Saskatchewan; [?] = not detected despite monitoring, as indicated by accompanying reference(s).

(Table 4), *R. conicus* is currently widespread on a number of invasive thistle species in all western provinces, including on *C. arvense* (McClay *et al.* 2002*a*). Unfortunately, it now also occurs on some native species of thistle, including *Cirsium undulatum* (Nutt.) Spreng. and *Cirsium flodmanii* (Rydb.) Arthur (Asteraceae) (McClay *et al.* 2002*a*).

Research on thistles also illustrates how non-native weeds may host new assemblages of both introduced and native arthropods. In addition to arthropods purposely introduced as biocontrol agents, non-native species of *Cirsium* harbour several species of arthropods that were accidently introduced from Europe or Eurasia. The European leaf beetle, *Cassida rubiginosa* Müller (Coleoptera: Chrysomelidae), was first collected in Canada in 1902 and has been reported from Alberta, Saskatchewan, and Manitoba (Klimaszewski *et al.* 2010), albeit not at prairie sites (McClay *et al.* 2002*a*, 2002*b*). The seed head fly, *Terellia ruficauda* (Fabricius) (Diptera: Tephritidae), occurs on *C. arvense* across Canada (McClay *et al.* 2002*a*). The seed head weevil, *Larinus planus* (Fabricius) (Coleoptera: Curculionidae), was found adventive on *C. arvense* in southern British Columbia, but was redistributed as a biocontrol agent in the four prairie provinces between 1989 and 1996 (McClay *et al.* 2002*a*). Establishment of *L. planus* from the redistribution, however, has been confirmed only for British Columbia and Alberta. Native arthropod species that feed on Canada's weedy thistles commonly include the painted lady butterfly, *Vanessa cardui* (L.) (Lepidoptera: Nymphalidae).

Feeding by native or adventive arthropods does not normally control weeds. Although larvae of *V. cardui* may locally defoliate patches of thistle, levels of herbivory over time and space are unpredictable because of the butterfly's irregular migratory patterns (Story *et al.* 1985). Despite the long-term and widespread occurrence in western Canada of the adventive beetles, *Brachypterolus pulicarius* (L.) (Coleoptera: Kateridae), *Rhinusa* (formerly *Gymnetron*) *antirrhini* (Paykull), and *R. neta* Germar (Coleoptera: Curculionidae), satisfactory control of yellow toadflax (*Linaria vulgaris* Mill. (Plantaginaceae)) has yet to be achieved (Sing *et al.* 2005). The reasons may be multiple, including the ability of yellow toadflax to compensate for flower or seed herbivory, or the presence of the adventive parasitoid, *Pteromalus microps* (Graham) (Hymenoptera: Pteromalidae). The latter attacks both *R. antirrhini* and the weevil *M. janthinus*, which was introduced as a biocontrol agent for toadflax (Volenberg and Krauth 1996; McClay and De Clerck-Floate 2002*b*). Thus, similar to weeds introduced from Europe with some of their insect herbivores, the insects themselves may arrive in North America with their natural enemies. Because feeding by endemic arthropods does not normally control weeds, biocontrol relies upon the deliberate introduction of arthropods that have been screened for both host specificity and efficacy.

Arthropod Introductions for Arthropod Pest Biocontrol

Whereas rangelands tend to be relatively stable environments, annual cropping systems are subjected to considerable disturbance. The type of crop in a field also commonly is changed on an annual cycle ("crop rotation") to prevent the buildup of weed, disease, and insect pest populations. Tillage for seedbed preparation or weed control is common. Harvesting itself, with the removal of most of the plant material from the field, is another major disturbance.

These disturbances hinder the establishment and efficacy of biocontrol agents, and cost-effective chemical methods are available to manage weed and insect pests. Thus, there has been very limited use of biocontrol within crop systems in Canada compared with that for weed control on rangelands. In total, only 19 species of parasitic insects have been

Table 5. Releases (R) of non-native parasitoids in classical biological control programs for insect pests of crops in the prairies of Canada. Parasitoids that have moved to the prairies adventively also are included (M). Established species are denoted with an asterisk (*). Underlined targets are native.

Target (Common Name) Biocontrol agent (Family) [type of release]	Site of Occurrence	Reference
Adelphocoris lineolatus **Goeze (Alfalfa plant bug) – on alfalfa**		
•*Peristenus adelphocoridis* Loan (Braconidae) [R]	For all agents, Saskatoon, SK	For all agents, Soroka and Carl 2002
•*Peristenus digoneutis* Loan (Braconidae) [R]		
•*Peristenus rubricollis* Thompson (Braconidae) [R]		
Agromyza frontella **Rondani (Alfalfa blotch leaf miner) – on alfalfa**		
•*Dacnusa dryas* Nixon (Braconidae)* [M]	•southern AB	•Meers 2010
Cephus cinctus **Norton[1] (<u>Wheat stem sawfly</u>) – on wheat**		
•*Collyria coxator* Villers (Ichneumonidae) [R]	•Swift Current, SK; Lethbridge, AB	•Smith 1931
Ceutorhynchus obstrictus **Marsham (Cabbage seedpod weevil) – on *Brassica* spp.**		
•*Stenomalina gracilis* Walker* (Pteromalidae) [M]	•southern AB	•Dosdall *et al.* 2009
•*Trichomalus perfectus* Walker (Pteromalidae) [R]	•southern coast and interior of BC	•Gibson *et al.* 2005
•*Mesopolobus morys* (Walker) (Pteromalidae) [R]	•southern coast and interior of BC	•Gillespie *et al.* 2006
Diuraphis noxia **Kurdjumvo (Russian wheat aphid) – on cereals**		
•*Aphelinus varipes* Foester (Aphelinidae) [R]	•Lethbridge, AB	•Olfert *et al.* 2002
•*Leucopis* spp. (Chamaemyidae) [R]	•southwestern SK	•Yu 1992
Delia radicum **L. (Cabbage root fly) – all agents released in 1950s in cole crops**		
•*Phygadeuon trichops* Thomson (Ichneumonidae) [R?]	•eastern Canada	For all agents, Hemachandra *et al.* 2005
•*Aphaereta* sp. (Braconidae) [R?]	•eastern Canada	
•*Trybliographa rapae* Westwood (Eucoilidae)*,[1] [RM?]	•eastern Canada	
•*Aleochara bilineata* Gyllenhall (Staphylinidae)*,[1] [RM?]	•prairies, widespread	
•*A. bipustulata* L.[2] [R?]	•prairies, widespread	
Hypera postica **Gyllenhal (Alfalfa weevil) – on alfalfa**		
•*Perilitus rutilus* Nees (Braconidae) [R]	•AB	•Loan 1958

***Lygus* spp. (Lygus bugs) – on alfalfa**		
•*Peristenus digoneutis* Loan (Braconidae) [R]	•Saskatoon, SK	•L. Braun, pers. comm.
***Mamestra configurata* Walker (Bertha armyworm) – on canola**		
•*Eurithia consobrina* Meigen (Tachinidae) [R]	•MB	•Mason *et al.* 2002
•*Microplitis mediator* Haliday (Braconidae) [R]	•SK, AB	•Turnock and Carl 1995
***Oulema melanopus* L. (Cereal leaf beetle) – on cereals**		
•*Tetrastichus julis** Walker (Eulophidae) [M]	•AB	•Cárcamo *et al.* 2007
	•released in north central MB from AB population	•HC, T. Larson, L. Dosdall, and J. Gavloski, unpublished
***Ostrinia nubilalis* Huebner (European corn borer) – on corn**		
•*Trichogramma brassicae* Bezdenko (Trichogrammatidae) [R][3]	•southern AB	•Yu *et al.* 1994
***Phyllotreta* spp (Flea beetles) – on canola**		
•*Townesilitus bicolor* Wesmael (Braconidae) [R]	•southern MB	•Wylie 1988
***Sitodiplosis mosellana* Gehin (Orange wheat blossom midge) – on wheat**		
•*Macroglenes penetrans* Kirby (Pteromalidae)* [M]	all agents released in SK	•Doane *et al.* 2002
•*Platygaster tuberosula* Kieffer (Platygastridae)* [R]		•Olfert *et al.* 2009
•*Platygaster* spp. (Platygastridae)		•Olfert *et al.* 2003
•*Euxestonotus error* Fitch (Platygastridae) [R]		•Carl and Affolter 1984
***Sitonia cylindricollis* (Fahr.) (Sweet clover weevil) – on sweet clover**		
•*Microctonus aethiops* Nees (Braconidae) [R]	•southern MB	•Loan 1957
•*Pygostolus falcatus* Nees (Braconoidae) [R]	•Brandon, MB	•Loan 1961
•*Perilitus rutilus* Nees (Braconidae) [R]	•southern MB	•Loan and Holdaway 1961*b*
•*Microctonus* sp. (Braconidae) [?]	•southern MB	•Loan and Holdaway 1961*b*

[1] Origin uncertain but generally considered native; see text.

[2] *Aleochara* bipustulata species complex could not have been separated, given taxonomy of the time.

[3] Released as an inundative agent.

[?] Insufficient records in the literature to determine identity of species released or origin uncertain;

RM? = could be Holarctic; R = intentional release, M = migration: species dispersed on its own or introduced accidentally.

purposely introduced to western Canada for the biocontrol of crop pest arthropods (Table 5). In the following two subsections, we provide an overview of arthropods that have become established (or may be established) in western Canada following their deliberate introduction as biocontrol agents of crop pests in Canada. We also include species that have emigrated from the United States, following their release in that country as biocontrol agents. The first subsection reviews agents released to control insect pests that are native to Canada (neoclassical biocontrol). The second subsection reviews agents released to control insect pests of exotic origin (classical biocontrol).

Arthropod Introductions against Native Pests

Examples of neoclassical biocontrol in western Canada include programs to control wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae); bertha armyworm, *Mamestra configurata* Walker (Lepidoptera: Noctuidae); and lygus bugs, *Lygus* spp. (Hemiptera: Miridae).

Wheat stem sawfly. One of the earliest attempts in Canada to introduce an arthropod for biocontrol in a field crop was against the wheat stem sawfly, *C. cinctus*. Although there is some debate (Ivie and Zinovjev 1996), most researchers consider this species to be native to North America. The parasitic wasp, *Collyria coxator* (Villers) [= *calcitrator* (Gravenhorst)] (Hymenoptera: Ichneumonidae), was imported from England and released near Swift Current, Saskatchewan, in 1930, but did not become established (Smith 1931). From 1937 to 1940, it was released against the European wheat stem sawfly (*C. pygmaeus* L.) in southern Ontario, where it became established and eventually controlled this pest (Turnbull and Chant 1961). *Collyria* species deposit a single egg on a sawfly egg. The newly hatched wasp larva penetrates the sawfly larva and slowly develops inside the host to overwinter as a mature wasp larva. The larva completes development in late spring or early summer of the following year, killing the mature sawfly larva. Recently, a new species, *Collyria catoptron* Wahl (Hymenoptera: Ichneumonidae), was described from the arid grasslands of northern China and currently is being evaluated for release to complement biocontrol programs for the wheat stem sawfly in the Northern Great Plains of North America (Wahl *et al.* 2007).

Bertha armyworm. This insect is a sporadic pest of broadleaf crops in western Canada, particularly brassicaceous crops, for example, canola, *Brassica napus* L. (Brassicaceae). In 1986 and 1987, *Eurithia consobrina* Meigen (Diptera: Tachinidae) was released in Manitoba near the communities of Kenville, Dauphin, and Glenlea. This fly is a common parasitoid of *Mamestra brassicae* (L.) (Lepidoptera: Noctuidae), a Eurasian species closely related to *M. configurata*, on which it was hoped the fly would become established. However, it was not detected in surveys from 1986 to 1992 at Kenville and Dauphin (Turnock and Carl 1995). The wasp *Microplitis mediator* (Haliday) (Hymenoptera: Braconidae) is a common larval parasitoid of *M. brassicae* in Europe (Lauro *et al.* 2005). From 1991 to 1999, specimens collected from Switzerland were released in Saskatchewan (Mason and Young 1994) and in Alberta in 1999 (J. Otani, pers. comm. with P. Mason; see Mason *et al.* 2002); however, it has not been recovered (Mason *et al.* 2002).

Lygus bugs. Native plant bugs in the genus *Lygus* (Hahn) are a serious pest of seed alfalfa, *Medicago* spp. (Fabaceae), and intermittent pests of canola. *Peristenus digoneutis* Loan (Hymenoptera: Braconidae) is a European species of parasitic wasp that has controlled populations of lygus bugs in the United States. In 2007, it was released in field cages near

Saskatoon, but establishment was not detected (L. Braun and J. Soroka, pers. comm. with HC). This parasitoid is discussed further in the next section, in relation to the control of exotic pests.

Arthropod Introductions against Exotic Pests

Examples of classical biocontrol in western Canada include programs to control, in descending order of vulnerable crop area, orange wheat blossom midge, *Sitodiplosis mosellana* Gehin (Diptera: Cecidomyiidae); cereal leaf beetle, *Oulema melanopus* L. (Coleoptera: Chrysomelidae); Russian wheat aphid, *Diuraphis noxia* Kurdjumvo (Homoptera: Aphididae); green peach aphid, *Myzus persicae* (Sulzer), and other aphids (Homoptera: Aphididae); cabbage root fly, *Delia radicum* L. (Diptera: Anthomyiidae); cabbage seedpod weevil, *Ceutorhynchus obstrictus* Marsham (Coleoptera: Curculionidae); flea beetles, *Phyllotreta* spp. (Coleoptera: Chrysomelidae); *Sitona* spp. (Coleoptera: Curculionidae); alfalfa weevil, *Hypera postica* Gyllenhal (Coleoptera: Curculionidae); alfalfa plant bugs (*Adelphocoris lineolatus* Goeze, *A. superbus* Uhler (Hemiptera: Miridae); alfalfa blotch leaf miner, *Agromyza frontella* Rondani (Diptera: Agromyzidae); and European corn borer, *Ostrinia nubilalis* Huebner (Lepidoptera: Crambidae).

Orange wheat blossom midge. This pest first was reported from Manitoba in 1901 (Fletcher 1902), but was not considered a wheat pest until 1983 (Olfert *et al.* 1985) (Fig. 5A). The adventive European parasitoid *Macroglenes penetrans* (Kirby) (Hymenoptera: Pteromalidae) (Fig. 5B) has effectively followed the midge on the Canadian prairies and co-occurs with this pest in up to 95% of midge-infested fields (Olfert *et al.* 2009). The parasitoid reduces the midge population on average by 45% and saved the wheat industry an impressive $248 million in the 1990s by lowering pest numbers below economic threshold (Olfert *et al.* 2009), thus avoiding the need for insecticide applications. The European parasitoids *Euxestonotus error* Fitch and *Platygaster tuberosula* (Kieffer) (Hymenoptera: Platygasteridae) were released in Saskatchewan in an attempt to increase levels of parasitism to the 65% reported for European regions. Only *Platygaster tuberosula* became established in the province (Doane *et al.* 2002). Although the released *P. tuberosula* came directly from Europe after regulatory approval was obtained for its release in Canada, *E. error* was released in Saskatchewan from an adventive population of the parasitoid found in wheat fields in the Okanagan Valley of British Columbia (Doane and Masner 1991). Hence, *E. error* is also established in Canada.

Cereal leaf beetle. This Eurasian species is a serious pest of cereal crops throughout North America, and biocontrol is the primary tool to manage it (Haynes and Gage 1981) (Fig. 6A). The European parasitoid *Tetrastichus julis* Walker (Hymenoptera: Eulophidae) (Fig. 6B) was released in eastern North America. Phillip (2007) relocated the parasitoid from Montana to British Columbia in 2002, where it is established. It effectively reduces larval populations and disperses to follow the beetle to new fields. This parasitoid came with the beetle into Alberta (Cárcamo *et al.* 2007) from an unknown source and currently kills about 30% of the pest in some populations near Lethbridge (Dosdall *et al.* 2011). Current efforts are under way (HC, T. Larson, L. Dosdall, and J. Gavloski, unpublished) to relocate it to west-central Manitoba, where the beetle was recently found (Dosdall *et al.* 2011).

Russian wheat aphid. This aphid was considered a potential serious pest of wheat and other cereal crops in southern Alberta in the late 1980s. Collections of the parasitoid

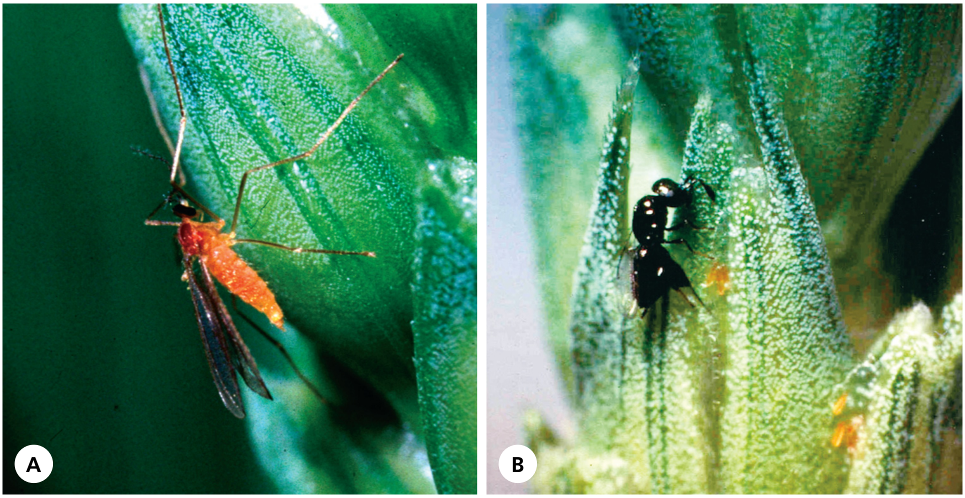

Fig. 5. The orange wheat blossom midge, *Sitodiplosis mosellana*, a serious pest of wheat in the prairies (A) that is partly controlled by the adventive parasitic wasp, *Macroglenes penetrans* (B). Photos courtesy of Agriculture and Agri-Food Canada, Saskatoon.

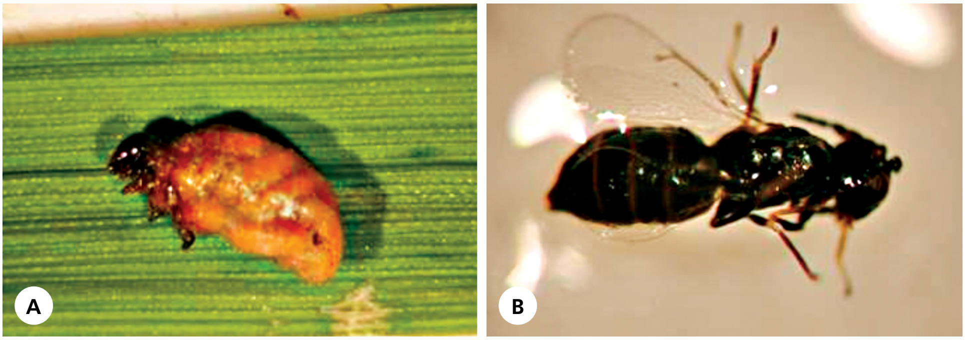

Fig. 6. Fourth instar larva (A) of the cereal leaf beetle, *Oulema melanopus*, with symptoms of parasitism by the parasitic wasp, *Tetrastichus julis* (B). Photos by T. Larson, Agriculture and Agri-Food Canada, Lethbridge.

Aphelinus varipes Foester (Hymenoptera: Aphelinidae) from Kazakhstan were released in southern Alberta and Saskatchewan after Yu (1992) determined it differed sufficiently in niche exploitation from the native *Aphelinus* near *varipes* species. Also released were the flies *Leucopis atratarsis* Tanasijtshuk (near Shaunavon, Saskatchewan) and *Leucopis ninae* Tanasijtshuk (Diptera: Chamaemyidae) (near Lethbridge, Alberta), whose larvae prey on this pest (Olfert *et al.* 2002). None of these three biocontrol agents was recovered in post-release monitoring in 1995 (Olfert *et al.* 2002).

Green peach aphid and other aphid spp. A number of aphid species, including *Mysus persicae*, are cosmopolitan in distribution. They do not overwinter in Canada, but are introduced to the prairies each spring on winds from the southern United States. Populations

Fig. 7. *Coccinella septempunctata* L. (sometimes referred to as C7), a generalist predator released for control of aphids in the USA and now widespread in North America, where it displaces native lady bird beetles. Photo by H. Goulet of Agriculture and Agri-Food Canada, Ottawa.

can reach pest status in cereals, alfalfa, pulses, brassicaceous crops, and potatoes, *Solanum tuberosum* L. (Solanaceae). The seven-spotted lady beetle, *Coccinella septempunctata* L. (C7) (Coleoptera: Coccinellidae) (Fig. 7), was introduced to the eastern United States to control aphids, where it became established in 1973 (Angalet *et al.* 1979). Its range expanded into the prairies (with some human-assisted dispersal, intentional and accidental). It was reported from Manitoba in 1988 (Matheson 1989) and in southern Alberta in 1992 (Yu *et al.* 1994). Turnock *et al.* (2003) provided evidence that this species is linked with the decline of a number of native coccinellid species, and Evans (2004) demonstrated habitat displacement of native species (also see summary by Acorn 2007).

The multicoloured Asian lady beetle (*Harmonia axyridis* Pallas) (Coleoptera: Coccinellidae) (Fig. 8) was introduced for aphid biocontrol in the United States as early as 1916. Although these initial releases were apparently unsuccessful (Gordon 1985), populations were reported in 1988 in the southeastern United States. It is unclear whether they derived from intentional or accidental introductions (Koch and Galvan 2008). The beetle is now known from Manitoba (Wise *et al.* 2002) and is expected to expand its range farther west. This species also has affected guilds of native/exotic coccinellids in the United States (Koch and Galvan 2008) and may be causing declines of *C. septempunctata* in the Ottawa region of Ontario (H. Goulet, pers. comm. with HC). Similar effects can be expected in the prairies, particularly in the semi-treed parkland region, which more closely resembles the habitat for *H. axyridis* in its native range (Koch and Galvan 2008).

Cabbage maggot. *Delia radicum* is a European pest of several vegetable cole crops and canola, particularly in the more humid portions of the Canadian prairies (Soroka *et al*. 2002). Classical biocontrol was attempted in the 1950s (see review and citations by Andreassen *et al*. 2007) after the parasitoid fauna of *Delia* was compared between Canada and Europe (Wishart 1957). On the basis of their apparent absence in Canada, putative releases were made for three species of parasitic wasps (*Phygadeuon trichops*

Fig. 8. *Harmonia axyridis* Pallas, the multicoloured Asian lady beetle or Halloween lady bug, another invasive species introduced for aphid control to eastern North America. It is present in Manitoba and is expected to negatively affect the assemblage of native lady bird beetles in western Canada. Photo by H. Goulet, Agriculture and Agri-Food Canada, Ottawa.

Thomson (Hymenoptera: Ichneumonidae); *Aphaereta* sp. (Hymenoptera: Braconidae); *Trybliographa rapae* Westwood (Hymenoptera: Eucoilidae)) and two species of parasitoid beetles (*Aleochara bilineata* Gyllenhal and *A. bipustulata* L. (Coleoptera: Staphylinidae)). A reassessment, however, determined that (1) *T. rapae* and *A. bilineata* were already present in Canada under different names; (2) the *Aphaereta* species released was not known and, apparently, like *P. trichops*, did not become established (McLeod 1962); and (3) *A. bipustulata* could not be distinguished from similar species (Klimaszewski 1984). Recent studies have determined that *A. bipustulata* is not present in Canada (Hemachandra *et al.* 2005, 2007), and it is currently being considered for use as a classical biocontrol agent. Its potential effect on non-target insect species may be a concern because adults attack related species. However, the actual risk may be minimal, given the preference of the beetle for only certain habitats (Andreassen *et al.* 2009). Natural enemies of cabbage maggot on the prairie reported by Hemachandra *et al.* (2005) include two undetermined species of *Phygadeuon*, *Aphaereta minuta* (Nees), *T. rapae*, *Aleochara verna* Say, and *A. bilineata*, as well as a species of *Trichopria* (Hymenoptera: Proctotrupidae). It is unclear whether these species became established following intentional releases or accidental introductions, or if they are endemic.

Cabbage seedpod weevil. This beetle is a serious pest of *Brassica* seed crops, particularly canola in southern Alberta and Saskatchewan (Dosdall *et al.* 2002), where it often requires chemical insecticide control (Cárcamo *et al.* 2005). Twelve species of parasitoid wasps (Hymenoptera: Chalcidoidea), including species native and adventive to North America, have been reared from *C. obstrictus* collected from the prairies of Canada. Three European species have been released in British Columbia: *Trichomalus perfectus* (Walker), *Mesopolobus morys* (Walker), and *Stenomalina gracilis* (Walker) (Pteromalidae). Only the latter species has been recovered, near the original release sites in southwestern British Columbia (Gibson *et al.* 2006; Gillespie *et al.* 2006) and from canola pods collected in Alberta (Dosdall *et al.* 2009).

Flea beetles. *Phyllotreta cruciferae* (Goeze) and *P. striolata* (Fab.), from Europe and Eurasia, respectively, are the most serious chronic pests of canola seedlings in North America (Lamb 1984). There has been limited biological control work on these pests (reviewed in Soroka and Elliot 2011). However, the parasitoid wasp *Townesilitus bicolor* (Wesmael) (Hymenoptera: Braconidae) was introduced from central Europe to Manitoba at Glenlea and Grandview (20 km south of Winnipeg) several times but failed to establish (Wylie 1988).

***Sitona* weevils.** The genus *Sitona* includes species of broad-nosed weevils that feed on the foliage and root nodules of many legume species. The pea leaf weevil, *Sitona lineatus* (L.) (Coleoptera: Curculionidae), was recently reported on the prairies (Vankosky *et al.* 2009). The sweet clover weevil, *Sitona cylindricollis* (Fahr.), and the clover root curculio, *Sitona hispidulus* (F.), are both widespread, the latter a pest of alfalfa (Bright 1994). A biocontrol program for *Sitona* species, mainly targeting the sweet clover weevil, was started in 1952 (Loan 1971). From 1952 to 1958, releases were made in Manitoba of the wasps *Microctonus aethiops* (Nees), *Perilitus rutilus* (Nees), and *Pygostolus falcatus* (Nees) (Hymenoptera: Braconidae) and of the fly *Campogaster exigua* (Meigen) (Diptera: Tachinidae) (Loan and Holdaway 1961*a*, 1961*b*). *Pygostolus falcatus* was reared in two consecutive years from sweet clover weevils collected near Brandon, Manitoba. The other species were not found and assumed to have not become established (Loan 1961). Later collections did not support reports of *P. falcatus* establishment in Manitoba. However, it was recovered at low densities from the sweet clover weevil and also from *Sitona lineellus* Bonsdorff near Belleville, Ontario, near another release site (Loan 1965).

Alfalfa weevil. *Hypera postica* is a global pest of alfalfa. In 1958, about 2,000 alfalfa weevils were exposed to *P. rutilus* (a wasp that parasitizes *Sitona* spp. in Europe), and they were released in the Milk River Valley south of Lethbridge, Alberta. It was hoped that the parasitoids had attacked *H. postica* and might establish a population on this pest, but no parasitoids were subsequently recovered (Loan 1958). In 1970, releases of the parasitoid wasps *Microctonus aethiops* (Nees) (Hymenoptera: Braconidae) (Agriculture Canada 1971) and *Bathyplectes anurus* (Thoms.) (Hymenoptera: Ichneumonidae) resulted in established populations in southern Ontario to supplement parasitism of *H. postica* by *Bathyplectes curculionis* (Thoms.), which is widespread in eastern Canada and the United States. It is not known if any of these three species occur in the Canadian prairies.

Alfalfa plant bugs. *Adelphocoris lineolatus* and *A. superbus* are pests of seed alfalfa crops. They are parasitized by several native species of the wasps *Peristenus* spp. (Goulet and Mason 2006), but at very low levels, e.g., 0–4% for *P. pallipes* in Saskatchewan (Craig and Loan 1987). *Peristenus braunae* Goulet (= *P. pallipes*, Goulet and Mason 2006) is a native species that is active in the spring. It parasitizes *Adelphocoris* plant bugs in southern Alberta and may cause higher rates of parasitism in some regions (HC, C. Herle, and H. Goulet, unpublished). Several releases of the European species *P. adelphocoridis* Loan, *P. digoneutis*, and *P. rubricollis* Thompson have been made in Saskatchewan, but with no evidence of establishment (Soroka and Carl 2002). *Peristenus digoneutis* mainly parasitizes lygus bugs. It has emigrated from the northeastern United States into southern Ontario and Quebec, where it likely attacks *Adelphocoris* species.

Alfalfa blotch leaf miner. *Agromyza frontella* is a minor pest of irrigated alfalfa that has been reported in the county of Newell in southern Alberta. The parasitoid wasp *Dacnusa dryas* Nixon (Hymenoptera: Braconidae) was reported from this region in 2008 and may be limiting the spread of *A. frontella* to other seed alfalfa districts (Meers 2010).

European corn borer. This pyralid moth has been a pest on many crops in eastern Canada since the 1920s. It was first reported in Alberta in 1956 near Medicine Hat (Harper and Lily 1956). It reappeared in Alberta in 1981 and has been present in the province ever since (Struble *et al.* 1987). Mass releases of the parasitoid wasp *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae), collected in France, were made against this pest in southern Alberta, but there is no evidence of establishment (Yu and Byers 1994). In a laboratory study, Babendreier *et al.* (2003*a*) reported high levels of egg parasitism of non-target Lepidoptera species, but minimal effects were observed under cage and field conditions in Switzerland (Babendreier *et al.* 2003*b*).

Ecological Impacts of Biocontrol Arthropod Establishment

The long-term ecological outcomes of biocontrol introductions for either weed or arthropod pest management remain largely unknown. First, a lack of resources has prevented, in many cases, a continued follow-up of released organisms to determine whether they have become established. Second, there are few population-level, community-level, and trophic interaction studies to assess the long-term sustainability of biocontrol, or its effects on ecosystem components and processes. Third, post-release assessments can be hampered by a lack of taxonomic knowledge. The biocontrol agent may be misidentified at the time of release, and subsequent monitoring programs may confuse the agent for species (adventive or native) that were already present at release sites. Taxonomic concerns are most relevant for biocontrol programs of crop pests. Parasitoid agents develop within the insect host (and are thus hard to detect), may be closely related to native species, and often require a high level of expertise to identify. For most weed biocontrol projects, the arthropod agent is readily apparent and/or its feeding damage is characteristic. Thus, agent establishment on weeds can be reliably assessed during post-release monitoring by field staff without formal entomology training.

For weed biocontrol within our more natural agroecosystems, the possible direct and indirect impacts of introduced biocontrol arthropods on non-target, native plant species is of growing concern. This has been fuelled, in part, by a change in societal values. Consider the example of the seed head weevil, *Rhinocyllus conicus*. In 1968, this European species was released into North America to control the introduced weedy thistle species *Carduus nutans* and *C. acanthoides*. Scientific information on the insect's host range collected prior to its release predicted that *R. conicus* could potentially feed and develop on native North American thistle species (tribe, Cardueae), which was understood and accepted by the regulatory agencies of the day. However, when feeding subsequently was reported by the weevil on native thistle species (Louda *et al.* 2003), this issue became highly controversial and contributed to a global re-examination of how the risks and benefits of classical biocontrol are weighed when deciding whether to introduce a foreign arthropod agent. The root of this controversy is not the underlying scientific principles and accuracy of host range assessment in biocontrol. Rather, it reflects the greater value that society now places on the natural environment and, thus, what constitutes acceptable risk to native species (Hoddle 2003). Of particular concern is the risk that weed biocontrol agents may pose to threatened and endangered native plant species that may be closely related to the target weed.

Agents released to control crop pests in Canada thus far seem to pose little risk to non-target species. Of the approximately 19 species reported to have been released on the Canadian prairies, only one has been confirmed as established. However, "absence of evidence is not evidence of absence" and little effort has been devoted to assess establishment success, let alone non-target attack. Interestingly, most of the common exotic species that attack crop pests (e.g., *Coccinella septempunctata*, *Harmonia axyridis*, *Dacnusa dryas, Stenomalina gracilis*, *Macroglenes penetrans*, *Tetrastichus julis*) are adventive, that is, have become established following dispersal from other regions. The lady beetle, *C. septempunctata* (Fig. 7), has reduced the dominance of some native coccinellid species in cultivated systems (e.g., *C. transversoguttata richardsonii* Brown in alfalfa; see Turnock *et al.* 2003) or has forced them into marginal, ancestral native habitats, such as sand dunes (Acorn 2007). However, in terms of biodiversity, the prairie arthropod community is now richer, albeit its structure and evenness has changed with the establishment of *C. septempunctata*. The effects of this latter species are not unexpected, because it is a generalist predator. However, there has been a paradigm shift away from the use of predators (which tend to be more generalist feeders) toward selection of biocontrol agents that are more host specific, that is, parasitoids.

Of approximately 19 releases, only *Platygaster tuberosula*, deliberately released for wheat midge control in Saskatchewan, is known to be established. The adventive species *T. julis* (Fig. 6B) and *M. penetrans* are abundant enough to potentially interact with native species. However, a preliminary environmental assessment indicates that *T. julis*, a parasitoid of the cereal leaf beetle (*Oulema melanopus*), is unlikely to affect native species (Hervet 2010). There are no native beetles closely related to *O. melanopus* that could be attacked by *T. julis*, and no other parasitoids are known to attack cereal leaf beetle larvae in the prairies. In laboratory studies, only *T. julis* was reared from *O. melanopus* and was not observed to attack a number of non-target species. Although these results are not conclusive, collectively they suggest that *T. julis* is unlikely to parasitize non-target beetle species or compete with native parasitoids for host species. To our knowledge, similar studies have not assessed the non-target effects of *M. penetrans* or any of the other non-native parasitoids established in the prairie region. According to a meta-analysis of life tables of herbivores, the chance of successful control by parasitoids is higher in systems with simplified food webs with little connectivity between the exotic species and the native community (Hawkins *et al.* 1999). Therefore, it can be argued that expected impacts of parasitoids, such as those imported for pest control in our highly simplified prairie crop ecosystems, are likely to be minimal (Hoddle 2003).

Future Directions

The next focus in classical biocontrol will be to more thoroughly assess the risks to non-target individuals in laboratory tests and also to elevate our predictions to the population and ecological community levels through innovative, intercontinent research. This can be done by studying the ecology and impact of potential foreign agents under natural conditions within their place of origin ahead of introduction. It also can be achieved by comparing the host use and impact predicted from pre-introduction laboratory or field tests to what actually occurs once the agent has been released in a new ecosystem. For example, the successful agent, *Mogulones crucifer*, released for houndstongue biocontrol (Fig. 2*a*, Table 1), was found to feed and develop on several species closely related to houndstongue (i.e., within the same plant family) during pre-release laboratory host-choice tests. This was confirmed for some of the native Canadian plant species after release in western Canada (Andreas *et al.* 2008). However, as is typical for host-specific, plant-feeding insects, the host range expressed under natural field conditions tends to be narrower than that expressed under the more unnatural, constrained conditions of laboratory testing. Thus, 10 years of monitoring for non-target feeding by *M. crucifer* since its release shows that the agent still prefers its host weed over non-target native plants that were deemed at risk during pre-introduction testing. Furthermore, the preference appears to be sustained even after the agent has severely reduced populations of its host plant. Currently, monitoring is being extended to look at the population level effects of any non-target feeding that may occur, because in the end, feeding may or may not be important to the survival and functioning of non-target populations or of the natural ecological communities that house them.

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