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Establishment and impact of *Galerucella calmariensis* L. (Coleoptera: Chrysomelidae) on *Lythrum salicaria* L. and associated plant communities in Michigan

Douglas A. Landis,[a,*] Donald C. Sebolt,[a] Michael J. Haas,[a,1] and Michael Klepinger[b]

[a] *Department of Entomology, Michigan State University, E. Lansing, MI 48824, USA*
[b] *Michigan Sea Grant Extension, 334 Natural Resources, Michigan State University, East Lansing, MI 48824, USA*

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Abstract

Purple loosestrife, *Lythrum salicaria* L. (Lythraceae) is an invasive wetland perennial plant of Eurasian origin that is widely established in North America and is considered a threat to native wetland flora and fauna. Two European beetles, *Galerucella calmariensis* L. and *Galerucella pusilla* Duft. (Coleoptera: Chrysomelidae) have been introduced and widely distributed in North America for biological control of *Lythrum salicaria*. Experimental releases of *Galerucella* spp. beetles were made in three locations in Michigan in 1994. In 1997 we initiated a project to rear, redistribute, and evaluate the impacts of *Galerucella* calmariensis in 19 additional sites throughout Michigan. *G. calmariensis* became established at 100% of the 24 release locations monitored in these studies and have persisted for up to seven years while *G. pusilla* apparently failed to establish. Large populations of *G. calmariensis* developed from each of the 1994 releases and caused 100% defoliation of *L. salicaria.* From 1995 to 2000, *L. salicaria* stem height was reduced 73–85%, percent plant cover was reduced 61–95%, and richness of nontarget plant species increased significantly at four out of five sites. By 2001, *L. salicaria* stem height and percent cover were reduced 38–81% and 32–74%, respectively, and nontarget plant species richness increased significantly at all five sites in contrast to the situation in 1995. Beetles have spread 3–10 km from these original release sites. Of the 19 additional sites monitored for 3–5 years post-release, 50% (4/8) of the 1997 releases have developed into large *G. calmariensis* populations and produced severe damage to *L. salicaria*. Thirty-three percent (2/6) of the 1998 releases have generated moderate impacts while all 1999 releases (5/5) remain without clear impacts. The successful establishment, spread, and impacts of *G. calmariensis* indicate the critical need for additional research on its role in the restoration of desirable plant communities in areas formerly dominated by *L. salicaria*.
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Keywords: *Galerucella calmariensis*; *Lythrum salicaria*; Weed biological control; Plant community change

1. Introduction

Purple loosestrife, *Lythrum salicaria* L. (Lythraceae) is a Eurasian perennial hydrophyte that has become widely distributed in North America (Stuckey, 1980). It is well adapted to invasion of disturbed sites, and following establishment, can form dense and highly persistent stands (Thompson et al., 1987). Because of its invasive nature, concerns regarding the potential impact of *L. salicaria* on native flora and fauna have frequently been expressed. Blossey et al. (2001) recently reviewed the literature on *L. salicaria* impacts and found evidence of negative effects on avian habitat, plant biodiversity, and wetland ecosystem function. Management of *L. salicaria* in North America relies on prevention where possible and a combination of cultural, chemical, and biological controls to manage established infestations (Mullin, 1998). Of these, biological control is considered to be the most promising for management of extensive infestations (Blossey

* Corresponding author. Fax: 1-517-353-5598.
E-mail address: landisd@msu.edu (D.A. Landis).
[1] Present address: Michigan State University, Department of Entomology, Trevor Nichols Research Complex, Fennville, MI 49408, USA.

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et al., 1994; Hight and Drea, 1991; Malecki et al., 1993)

In its native range, *L. salicaria* is a successful invader (Thompson et al., 1987), but stands do not generally persist due to a complex of insect herbivores that limit its growth and reproduction (Blossey, 1995). Efforts at biological control of *L. salicaria* in North America have included identification, evaluation, and importation of selected European natural enemies (Blossey et al., 1994). As part of this program, two Chrysomelid beetles, *Galerucella calmariensis* L. and *Galerucella pusilla* Duft. (herein jointly referred to as *Galerucella*) have been widely distributed in North America (Hight et al., 1995). Initial efforts to establish *Galerucella* in 10 states and six Canadian provinces in 1992–1993 were highly successful (Hight et al., 1995; McAvoy et al., 1997; Piper, 1996). Recent reports indicate that the *Galerucella* species have shown dramatic population increases and impacts on *L. salicaria* at some sites 3–5 years after release (Blossey and Skinner, 2000; Kaufman and Landis, 2000). Development of a mass rearing protocol (Blossey and Hunt, 1999) and its adaptation for use by wetland managers and educators (Klepinger et al., 1999; Loos and Ragsdale, 1998) has greatly enhanced the availability of these natural enemies. It is estimated that by 1999, 5 million *Galerucella* adults were released in 33 states and over 1500 wetlands nationwide (Blossey et al., 2001).

The impact of *L. salicaria* on associated plant communities has been a topic of debate (Blossey et al., 2001). Prior to the initial release of natural enemies, evidence indicated that *L. salicaria* was responsible for displacement of native plant communities (Mal et al., 1992; Thompson et al., 1987) and domination of the seed bank (Welling and Becker, 1990). However, in a review of the literature, Anderson (1995) concluded there was a lack of clear evidence that *L. salicaria* out competes native species in the field. Similarly, Hager and McCoy (1998) were critical of the biological control effort based in part on the argument that the negative effects of *L. salicaria* on wetland communities were not demonstrated. Subsequent studies have shown that *L. salicaria* can be highly competitive (Gaudet and Keddy, 1995; Weiher et al., 1996) and can replace *Typha* spp. under some circumstances (Mal et al., 1997; Weihe and Neely, 1997). Gabor et al. (1996) demonstrated an increase in native plant species following *L. salicaria* removal by herbicides and Brown and Mitchell (2001) documented the adverse affects of *L. salicaria* on pollination and seed set of the native *L. alatum*. Alternatively, Rachich and Reader (1999) found that *L. salicaria* seed was unable to germinate in undisturbed plots of *Phalaris arundinacea* L. but established readily in disturbed plots. They concluded that *L. salicaria* invasion may be dependent on disturbance that permits seedling establishment and insufficient herbivory to prevent seedling survival. Treberg and Husband (1999) failed to find evidence that plant-species richness was significantly impacted by the presence of relatively young stands (ca. 12 years) of *L. salicaria.* Most recently, Farnsworth and Ellis (2001) report a general lack of correlation of nontarget plant density, diversity, or richness indices with *L. salicaria* density but found a significant negative correlation of *L. salicaria* and nontarget species biomass. Thus, *L. salicaria* may dominate stands in terms of biomass and presumably ecological function, without producing changes in certain density, richness, or diversity indices.

In Michigan, experimental releases of *G. calmariensis* and *G. pusilla* were conducted in 1994 by Michigan Department of Natural Resources-Wildlife Division (MDNR) on three state-managed wildlife areas. These sites were initially monitored in 1995 (D. Dalgarn and G. Kantak, Saginaw Valley State University, unpublished data). Based in part on our observations of the establishment and initial impacts of *Galerucella* beetles at these sites, in 1997 the Purple Loosestrife Project at Michigan State University was initiated to further investigate the potential for biological control of *L. salicaria* in Michigan. As part of these efforts, we reinitiated monitoring of the original 1994 release sites and conducted rearing, redistribution, and evaluation of *G. calmariensis* on additional private and public lands throughout Michigan.

The objectives of the following studies were to: (1) document the establishment and population growth of *G. calmariensis* and *G. pusilla* in Michigan at the 1994 and 1997–1999 release sites, (2) to determine the impact of *Galerucella* spp. populations on the growth and reproduction of *L. salicaria*, and (3) to document changes in the associated plant community of selected sites.

2. Materials and methods

2.1. Sites and insects

Releases of *Galerucella* spp. described in this study were conducted in 1994 and 1997–1999. The 1994 releases were made by MDNR personnel on three state-managed wildlife areas; Shiawassee River State Game Area, Crow Island State Game Area, and Nayanquing Point Wildlife Area (Table 1). These locations were selected based on the presence of large expanses of *L. salicaria* and the desire to reduce its density to achieve wildlife management goals. Insects for 1994 releases were provided by B. Blossey, Cornell University and consisted of a mixture of adult *G. calmariensis* and *G. pusilla*. At the Shiawassee River location a single release was conducted and paired with a single control location located approximately 0.5 km away (Fig. 1). At Crow Island, two release sites named the 'Road' and 'Meadow' sites were created and paired with a single control site

Table 1
Site information for 1994–1999 releases of *Galerucella* against *L. salicaria* in Michigan

Initial release year, site name[a]	County	Latitude	Longitude	Site type	Date of initial (supplementary) release	Number released (stage)[b]	Species established, date determined
1994							
Crow Island SGA 'Road'	Saginaw	N 43 28.704′	W 83 54.194′	Drainage Ditch	6 July	875 (A)	*G. calmariensis* 5 July 2000
Crow Island SGA 'Meadow'	Saginaw	N 43 28.625′	W 83 53.934′	Wet Meadow	6 July	875 (A)	*G. calmariensis* 6 July 2000
Nayanquing Point WA 'Field'	Bay	N 43 46.454′	W 83 57.122′	Wet Meadow	6 July	875 (A)	*G. calmariensis* 7 July 2000
Nayanquing Point WA 'Marsh'	Bay	N 43 46.449′	W 83 57.188′	Impounded Marsh	6 July	875 (A)	*G. calmariensis* 7 July 2000
Shiawassee River SGA 'Cage'	Saginaw	N 43 19.735′	W 84 05.836′	Impounded Marsh	6 July	1750 (A)	*G. calmariensis* 10 July 2000
1997							
Lost Nation SGA 'Lake #2'	Hillsdale	N 41 49.588′	W 84 28.084′	Lake	23 May	6405 (A,E,L)	Not determined
					(24 June 1998)	5120 (A,E,L)	
Lost Nation SGA 'Rifle Range'	Hillsdale	N 41 51.340′	W 84 30.577′	Marsh	23 May	6070 (A,E,L)	Not determined
Waterloo SRA	Jackson	N 42 19.736′	W 84 10.617′	Stream	29 May	6020 (A,E,L)	Not determined
Saginaw–Gratiot SGA	Gratiot	N 43 14.836′	W 84 25.422′	Lake	2 June	5620 (A,E,L)	*G. calmariensis* 10 July 2000
St. Johns Marsh	St. Clair	N 42 40.050′	W 82 36.593′	Wet Meadow	3 June	8120 (A,E,L)	Not determined
Pointe Mouillee SGA 'Walpatich'	Monroe	N 42 01.715′	W 83 13.359′	Impounded Marsh	3 and 24 June	8070 (A,E,L)	Not determined
Lake Lansing North 'Boardwalk'	Ingham	N 42 45.938′	W 84 23.381′	Marsh	11 and 27 June, 3 July	14,510 (A,E,L)	Not determined
					(8 July 1998,	1120 (A,E,L)	
					23 June 1999,	20,000 (A)	
					1 July 1999)	2210 (A,E,L)	
MSU 'Avian Disease'	Ingham	N 42 42.744′	W 84 29.049′	Marsh	1 July	8810 (A,E,L)	*G. calmariensis* 17 July 2000
1998							
Allegan 'Hopkins'	Allegan	N 42 37.822′	W 85 58.370′	Wet meadow	29 May	7737 (A,E,L)	Not determined
Holland 'Windmill Island'	Ottawa	N 42 47.638′	W 86 05.711′	Lake	3 June, 14 July	6076 (A,E,L)	*G. calmariensis* 29 June 2000
Sleeping Bear Dunes 'Aral Rd.'	Benzie			Wet Meadow	26 June	9210 (A,E,L)	Not determined
East Reeds Lake	Kent	N 42 56.584′	W 85 35.187′	Marsh	9 July	7058 (A,E,L)	*G. calmariensis* 14 July 2000
West Reeds Lake	Kent	N 42 57.354′	W 85 36.735′	Marsh	9 July	7304 (A,E,L)	Not determined
South Lake	Washtenaw	N 42 24.287′	W 84 03.567′	Marsh	17 July	11,060 (A,E,L)	Not determined
1999							
Davisburg 'Millpond'	Oakland	N 42 45.094′	W 83 32.330′	Lake	12 May	3100 (A,E,L)	*G. calmariensis* 17 July 2000
Kellogg Biological Station	Kalamazoo	N 42 22.151′	W 85 26.705′	Marsh	18 May	4822 (A,E,L)	Not determined
					26 May	7203 (A,E,L)	
Grand River 'Riverside Park'	Ottawa	N 43 01.657′	W 86 02.218′	Lake	24 May	9442 (A,E,L)	Not determined
Kalamazoo River 'Sebolt Farm'	Calhoun	N 42 16.380′	W 84 50.250′	Marsh	27 May	10,657 (A,E,L)	*G. calmariensis* 11 July 2000
Grand River 'Boat Launch'	Ottawa	N 43 02.259′	W 86 04.950′	River	2 June	3709 (A,E,L)	Not determined
					14 July	4730 (A,E,L)	

[a] SGA, State Game Area; SRA, State Recreation Area; WA, Wildlife Area.
[b] 1994 values derived from Dalgarn and Kantak (unpublished data). 1997–1999 estimated numbers based on emergence from a sample of the cohort retained for greenhouse rearing.

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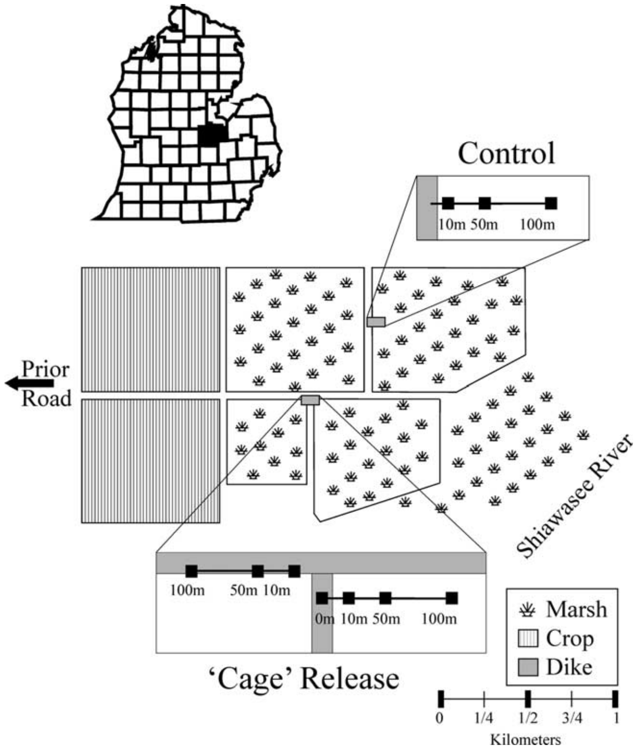

Fig. 1. Map showing the relationship of the 1994 *Galerucella* release and control sites at Shiawassee River State Game Area, Saginaw County, MI. Expanded views of each site indicate locations of permanent sampling quadrats.

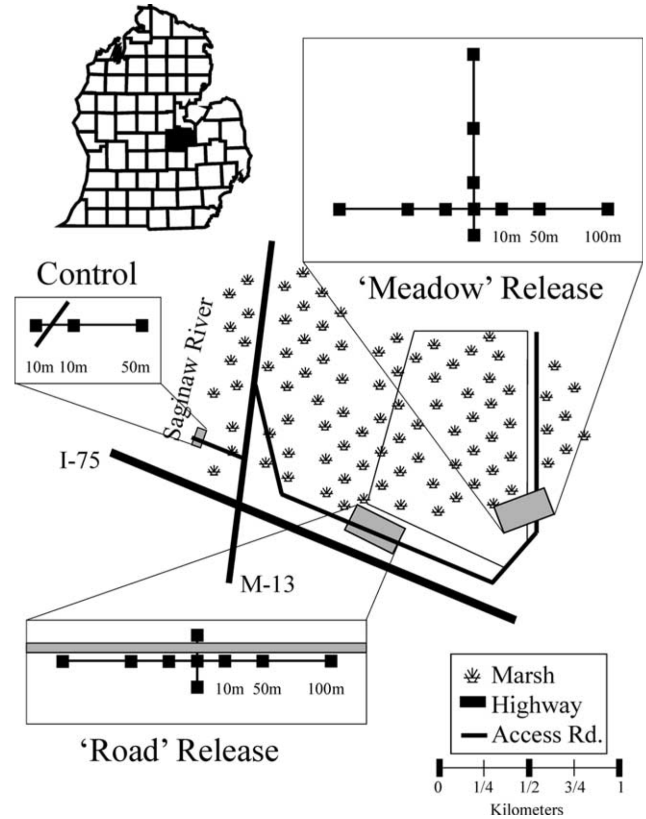

Fig. 2. Map showing the relationship of the 1994 *Galerucella* release and control sites at Crow Island State Game Area, Saginaw County, MI. Expanded views of each site indicate locations of permanent sampling quadrats.

approximately 0.75 km away (Fig. 2). At Nayanquing Point, two release sites named the 'Field' and 'Marsh' sites were also paired with a single control which was >1.0 km from either release site (Fig. 3). Insects were released by placing adults into $3.7 \times 3.7 \times 1.8$ m high Lumite field cages erected over dense stands of *L. salicaria*, or in one case, by placing adults into 1 m $\times$ 30 cm diameter sleeve cages secured around individual plants (Nayanquing Point 'Marsh'). GPS-derived coordinates for all release sites and the numbers and stages of insects liberated are shown in Table 1. All cages were removed on 24 July 1994 except for the Crow Island 'Road' cage that was removed on 24 September 1994. Attempts were made to establish 1 m^2 sample quadrats at 10, 50, and 100 m in each cardinal direction from the center of each release site. Due to site restrictions (deep water, cropped habitats, etc.) release sites contained 6–11 sample quadrats. Control sites were established with three sample quadrats (Figs. 1–3).

Sites for the 1997–1999 redistribution releases (Table 1) were selected based on loosestrife density, plant community composition, accessibility, lack of insecticide use, lack of permanent flooding, and the absence of selected nontarget plants (Klepinger et al., 1999). Redistribution sites were generally a minimum of 50 km from any previous release and contained no evidence of *Galerucella* life stages or damage. Insects for 1997–1999 releases were reared at Michigan State University (MSU) from insects provided by R. Wiedenmann, Illinois Natural History Survey (INHS). The INHS colony was originally obtained from B. Blossey and contained both *G. calmariensis* and *G. pusilla* (R. Wiedenmann, personal communication), however, only *G. calmariensis* has been identified from MSU-reared insects and thus was the only species released in 1997–1999. *G. calmariensis* were reared in large sleeve cages surrounding potted *L. salicaria* plants in the greenhouse using methods adapted from Blossey and Hunt (1999). New groups of plants were infested weekly over a period of 6–8 weeks beginning in April. This provided continuous production of *G. calmariensis* for release from mid May to mid July. Approximately three weeks after infestation, plants were arranged in cohorts based on larval stage of *G. calmariensis*. Cohorts were observed daily for adult emergence and plants were prepared for field release upon first observation of teneral adults. Stems and foliage with eggs or larvae were clipped and left in the sleeve cage for transport to the field. The pots containing prepupae and pupae, were covered with a smaller (10 cm high) sleeve cage to confine adults that emerged in transit. Releases were made by placing pots next to *L. salicaria* in the field and removing the sleeve cage, al-

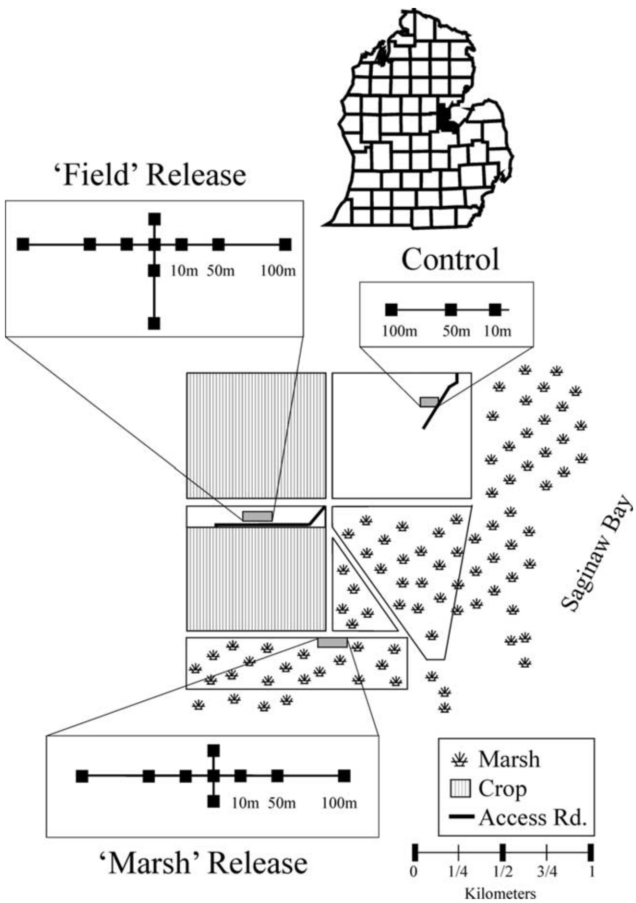

Fig. 3. Map showing the relationship of the 1994 *Galerucella* release and control sites at Nayanquing Point Wildlife Area, Bay County, MI. Expanded views of each site indicate locations of permanent sampling quadrats.

lowing newly emerged adults to disperse onto adjacent plants. Cut stems and foliage were placed on adjacent *L. salicaria* plants. Pots were recovered after 4–6 weeks and *L. salicaria* root crowns placed in plastic bags for disposal. At each site, approximately 20% of the available insects were released at each corner and the center of a 10×10 m release area. Sampling quadrats of 1 m^2 were established at these five locations and at 10 and 50 m in two cardinal directions, i.e., a 100 m transect through the center of the release area.

To estimate the numbers of insects released, not less than 20% of the plants in any release cohort were selected at random and retained in the greenhouse until beetle emergence was complete. Emerged beetles were counted daily and transferred to a fresh plant. Under greenhouse conditions these adults would begin to feed, mate, and oviposit depending on the length of time held. These plants and insects were added to a subsequent release cohort, which resulted in most releases containing some gravid females. The benefits of this system are that it minimized handling time and stress to individual beetles. Negative aspects are that the number of individuals released is estimated, and the requirement to transport and recover pots and root crowns from the field.

2.2. Insect and vegetation sampling

1995. The 1994 release sites were sampled in 1995 by Dalgarn and Kantak (unpublished data). *Galerucella* were censused by recording the number of adults, larvae, and egg masses detected in 30 person-minute searches conducted within the bounds of the initial 3.7 m^2 release area and within a 1.5 m radius of the sleeve release cages at Nayanquing Point. Thorough, untimed searches for the same life stages were conducted in the 1 m^2 transect plots. At all release and transect plots, a visual estimate of the percent cover of *L. salicaria* and percent foliage damage were conducted. No attempt was made to distinguish *Galerucella* damage from other defoliators, although the majority of plants with minor damage did not have skeletonized leaves characteristic of *Galerucella* larval feeding. Identical surveys were conducted at control sites on the same days that release sites were sampled. *Galerucella* monitoring was conducted on all sites between 19 and 21 June 1995.

Vegetation surveys were conducted at release sites, transect plots, and control sites on 7–9 August 1995, after *Galerucella* activity had declined. During this time most vegetation was at maximum biomass and *L. salicaria* was in bloom. The 3.7 m^2 release areas, 1 m^2 transect plots, and 1.5 m radius plots at sleeve and control sites were surveyed to determine: percent *L. salicaria* cover (seedling and mature plants), average height of mature *L. salicaria*, and percent cover of dominant nontarget vegetation.

1997–2001. *Galerucella* abundance and plant impacts were monitored in sample quadrats using standardized protocols (Blossey and Skinner, 2000). These protocols include a spring assessment to evaluate *Galerucella* abundance and damage and a late summer assessment to evaluate impacts on *L. salicaria*. For spring assessments, the number of *Galerucella* egg masses, larvae, and adults were evaluated by searching each quadrat for 1 person-minute per life stage. Percent *Galerucella* feeding damage, percent cover, number of stems, and height of the five tallest stems were also recorded for *L. salicaria*. Summer evaluations consisted of recording: percent cover, number of stems, and total number of inflorescences, for *L. salicaria*, as well as the height, number of inflorescences, length of terminal inflorescence, and number of flower buds per 5 cm of inflorescence for each of the five tallest *L. salicaria* stems. At selected sites, a minimum of 50 adult *Galerucella* beetles were collected by sweeping *L. salicaria* foliage in late June and early July and returned to the lab for species identification. To minimize variation in *L. salicaria* and *Galerucella* maturity among sites, southern Michigan counties were sampled first, progressing to more

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northern parts of the state. Sampling required 13–35 days to complete and was conducted from 28 May to 24 June and 4–17 September, 1997; 18 May to 8 June and 5–25 August, 1998; 3–28 June and 22 July to 13 August, 1999; 22 May to 19 June and 21 July to 24 August, 2000; and 31 May to 28 June and 31 July to 28 August, 2001, for spring and summer samples, respectively.

The above metrics were taken from selected 1994 release sites and from all 1997–1999 release sites. Exceptions occurred when plots were inaccessible due to flooding or when logistical constraints prevented sites from being visited in a timely fashion. To determine changes in the plant communities over time, we returned to the 1994 release sites on 31 July to 1 August, 2000 and 6–23 August, 2001 to conduct identical vegetation sampling to those performed in 1995. We attempted to rule out observer bias by having the 1995 observers conduct the plant community observations with us in 2000. These trained individuals then conducted the observations alone in 2001. In most cases the original 1994 plot markers were relocated. Where this was not possible, replacement sites were established by measurement from an existing 1994 marker.

Data analysis. *Galerucella* egg masses and larvae are reliably observed when present, however, adults effectively conceal themselves on cool, cloudy or windy days and adult counts may thus be biased. *Galerucella* counts between sites also are influenced by within-season timing, with sites visited early in the spring having a greater proportion of adults and eggs, while those visited later have more larvae. Thus, to provide a comparable picture of *Galerucella* abundance over sites and years, we report the mean number of all life stages present (egg masses + larvae + adults) per m^2. When egg masses are present, this represents a conservative estimate of the number of *Galerucella* per m^2 since individual egg masses average 5.8–7.8 eggs per mass (Kaufman and Landis, 2000). Because we were primarily interested in initial *Galerucella* establishment and population increase and not dispersal, the analysis was limited to the quadrats located closest to the point(s) of release. For 1994 releases we analyzed beetle populations at the 0 and 10 m quadrats resulting in an $n = 5$ for most sites. However, some release sites did not have quadrats established in all four cardinal directions, resulting in an $n = 3$ or 4 for some sites. We converted 1995 *Galerucella* counts at the release sites into beetles per m^2, however since these counts were done without time limits, they cannot be statistically compared to the 2000–2001 data. Thus, we report the mean ± SEM per m^2 for each site with no statistical comparisons. Finally, due to the rapid growth of *L. salicaria* in the spring, percent cover, number of stems, and height of the tallest stems varied widely between sites due in large part to sample timing and are not reported here.

We tested the hypothesis that vegetation characteristics (number of *L. salicaria* stems, percent cover, stem height, and nontarget species richness) did not change following *Galerucella* release. To do so we contrasted plant parameters in 1995 (year following initial release) to the same parameters in 2000 and 2001 in sites with and without *Galerucella* release. Sites varied in their prerelease characteristics and there was unequal replication within sites precluding the use of ANOVA across sites. Therefore, analyses were performed separately for each site. Means of vegetation characteristics were calculated for each site during each year and were contrasted using *t* tests (SAS Institute, 1996).

3. Results

3.1. *Galerucella establishment*

1994 Releases. Sampling in 1995 confirmed the presence of *Galerucella* in each of the release sites while no *Galerucella* life stages were detected at any of the control sites. Eggs and larvae were detected at all release sites and adults were also detected at the Crow Island ‘Road’ site. Total numbers of *Galerucella* life stages ranged from 0.4 ± 0.4 (mean ± SEM, $n = 5$) to 4.4 ± 4.1, $n = 5$ at the Crow Island ‘Meadow’ and ‘Cage’ sites, respectively. The Nayanquing Point ‘Field,’ ‘Marsh,’ and Shiawassee River ‘Cage’ sites contained 0.9 ± 0.5, $n = 5$; 1.1 ± 0.8, $n = 4$; and 4.2 ± 3.4, $n = 3$ total *Galerucella*, respectively.

Site visits in 1997 revealed limited *Galerucella* damage in all 1994 release sites, however, by 1998, impacts on *L. salicaria* were dramatic at Crow Island (Table 2). From the original site of release there was no live loosestrife foliage for ca. 100 m in either direction due to a combination of intense larval and adult feeding. As a consequence, beetle counts in the release area at Crow Island were low due to the lack of host plant material. Teneral adults were seen dispersing from this area to find new host plants for feeding. Timed counts of beetles flying over a 1 m line transect located 130 m from the site of release averaged 25.4 ± 2.3 beetles per minute. The nearest flowering plants were located 150–160 m from the center of the release area. Teneral adult feeding on these plants was intense. On one such plant, over 120 adults were collected in a few minutes and the collection did not appreciably deplete the population due to constant arrival of new individuals. Beetles, eggs, or larval damage were distributed throughout the contiguous purple loosestrife infestation extending 150–270 m from the release site.

By 1999, similarly large and damaging *Galerucella* populations were present at the Shiawassee River ‘Cage’ and Nayanquing Point ‘Marsh’ sites (Table 2). Again, the near complete lack of live *L. salicaria* foliage in the

Table 2
Evaluations of beetle establishment from 1994 releases of *Galerucella* beetles versus *L. salicaria* in Michigan

Year released, release site	Year	*N*	Life stages present, eggs, larvae, adults	Total number[a] *Galerucella* per m^2	Percent damage range
Nayanquing Point 'Field'	1999[b]	5	+ + −	1.8 ± 0.7	1–5
	2000	5	+ + +	113.8 ± 12.6	5–25
	2001	5	+ + +	47.6 ± 6.4	5–25
Nayanquing Point 'Marsh'	1999[b]	4	− − +	0.3 ± 0.3	75–100
	2000	4	+ − +	10.8 ± 3.8	75–100
	2001	4	+ + −	23.0 ± 2.7	5–25
Crow Island 'Road'	1998[b]	5	+ − +	1.6 ± 1.6	75–100
	1999	5	+ − +	7.8 ± 1.7	75–100
	2000	5	+ + +	36.0 ± 13.6	50–75
	2001	5	+ + +	20.6 ± 2.2	5–25
Shiawassee River 'Cage'	1999[b]	3	− − −	0.0 ± 0.0	75–100
	2000	3	+ + +	7.7 ± 7.7	5–25
	2001	3	+ + −	3.0 ± 3.0	5–25

[a] Egg masses + larvae + adults.
[b] Sampling in 1998–1999 was conducted in late June after larval defoliation. *Galerucella* were absent from the sampled sites in part due to a near complete lack of live *L. salicaria* foliage while surrounding areas contained large numbers of new adults.

sampled areas resulted in a low number of *Galerucella* detected, while surrounding areas contained large numbers of new adults, eggs, and larvae. In 2000, all sites were sampled earlier in the spring and showed higher numbers of *Galerucella* life stages. The Nayanquing Point 'Field' had 113.8 ± 12.6 total *Galerucella* per m^2, the highest recorded in this study. Samples of F_1 adults from all 1994 release sites in June 2000 revealed that only *G. calmariensis* was present in the populations (Table 1). Numbers of *Galerucella* declined at three of the four sites in 2001, increasing only at the Nayanquing Marsh site (Table 2).

1997–1999 Release sites. *Galerucella* population levels varied among sites and between years (Table 3). In the year following release, *Galerucella* density in spring evaluations ranged from 0.4 to 27.6 per m^2 (Aral Road and Waterloo, respectively). In most sites, all life stages could be detected (eggs, larvae, and adults), however, damage to *L. salicaria* was generally slight, typically 1–5%.

In the second year after release, populations of *Galerucella* increased in 11 of 19 sites (58%), declined in eight (42%), and remained unchanged from prior levels at one site. Densities ranged from undetectable to 55.2 per m^2. Spring damage to *L. salicaria* was still generally low in the second year post-release with the exception of Pointe Mouillee. In this site, *Galerucella* produced a large second generation in the year of release (1998). This apparently contributed to a large overwintering population and 75–100% defoliation of *L. salicaria* in the spring of 1999.

In the third year after release, populations of *Galerucella* increased in six of 14 sites (43%), remained unchanged from prior levels in four sites (29%), and declined in four sites (29%). Densities ranged from 0.2 to 53.2 per m^2 at the Lost Nations 'Rifle Range' and Pointe Mouillee sites, respectively, with spring damage still generally less than 5% with the exception of Pointe Mouillee where it reached 50–75%.

In the fourth year after release, populations of *Galerucella* increased in only one of eight sites (13%), remained unchanged from prior levels in four sites (50%), and declined in three sites (38%). Densities ranged from undetectable at Lake Lansing North to 53.2 per m^2 at Saginaw–Gratiot. With the exception of Lake Lansing North, eggs were detected at all sites confirming continued establishment four years after initial release.

3.2. *Lythrum salicaria* impacts

The 1997–1999 redistribution sites revealed a range of plant impacts one to four years after *Galerucella* release. An important caveat is that *L. salicaria* exhibits relatively large natural variation in height and inflorescence characteristics. The Lake Lansing North site illustrated this situation with ca. 20% shifts in plant parameter values between years. It is highly unlikely that the very low *Galerucella* densities ($\leqslant 4.0$ per m^2) and percent damage ($\leqslant 5\%$) could result in these changes (Table 3). For this reason, reliably discerning *Galerucella* impacts requires analysis of several insect and plant criteria.

Pointe Mouilee is a site where large numbers of *Galerucella* caused clear impacts on *L. salicaria*. Percent cover of *L. salicaria* dropped from its maximum of 75–100% in 1998 to 0 in 1999–2000, rebounding slightly to 1–5% in 2001. Plant height averaged 102–125 cm in 1997–1998 and has been reduced to 25–44 cm in 1999–2001, and since 1999 no flowering has occurred (Table 3). Lost Nations 'Lake #2' and Saginaw–Gratiot also have reduced plant height, and the lack of flowering is indicative of severe *Galerucella* damage. Sites such as St. Johns Marsh, Holland and South Lake may be showing early signs of impacts on *L. salicaria* including reductions in plant height and inflorescence characteristics,

Table 3
Spring beetle establishment and fall target plant impact from 1997–1999 releases of *Galerucella* beetles versus *L. salicaria* in Michigan

Year released, release site[a]	Year	*N*	Spring evaluations			Fall evaluations				
			Life stages present, eggs, larvae, adults	Total number[b] *Galerucella* per m^2	Percent damage, range	Percent cover, range	Mean stem height (cm)	Inflorescence characteristics (mean ± SEM)		
								Number/m^2	Length of terminal (cm)	Flower buds/5 cm of terminal
1997										
MSU 'Avian Disease'	1998	5	+ + +	10.4 ± 2.7	5–25	50–75	107.3 ± 3.4	10.8 ± 1.3	9.5 ± 3.9	21.7 ± 3.0
	1999	5	+ + −	5.0 ± 2.1	1–5	25–50	111.0 ± 4.9	9.9 ± 2.1	31.1 ± 3.3	28.4 ± 1.9
	2000	5	+ − −	4.2 ± 1.6	1–5	25–50	104.1 ± 2.7	3.3 ± 0.9	18.4 ± 2.5	26.3 ± 4.0
	2001	5	+ + +	1.2 ± 0.8	1–5	5–25	114.6 ± 3.8	4.4 ± 0.6	18.3 ± 4.5	25.6 ± 6.5
Lost Nations 'Rifle Range'	1998	5	+ − +	6.0 ± 2.5	1–5					
	1999	5	− − −	0.0	0	25–50	193.3 ± 8.3	16.8 ± 3.5	31.0 ± 3.0	38.2 ± 1.4
	2000	5	+ − −	0.2 ± 0.2	0		163.6 ± 4.0	5.8 ± 1.3	11.4 ± 2.7	30.8 ± 0.7
	2001	5	+ − −	0.6 ± 0.4	0	25–50	193.8 ± 7.5	14.0 ± 0.9	31.1 ± 4.8	30.8 ± 3.3
Lost Nations 'Lake #2'	1997	5				50–75	183.1 ± 4.9	10.8 ± 1.3	51.2 ± 2.1	31.8 ± 1.1
	1998	5	+ + +	2.6 ± 1.1	1–5	50–75	171.8 ± 2.7	15.3 ± 2.1	23.7 ± 1.8	15.1 ± 2.9
	1999	5	+ + +	8.2 ± 4.8	1–5	1–5	78.1 ± 23.5	5.0 ± 3.2	10.2 ± 3.9	25.0 ± 7.5
	2000	5	+ + +	14.0 ± 0.0	1–5	1–5	61.3 ± 5.7	0.0	0.0	0.0
	2001	5	+ + +	14.0 ± 7.9	1–5	1–5	50.0 ± 17.0	4.8 ± 4.8	4.8 ± 1.9	6.0 ± 6.0
Waterloo SRA	1998	5	+ + +	27.6 ± 5.9	1–5	50–75	142.0 ± 5.4	9.7 ± 1.2	17.9 ± 1.7	47.3 ± 5.8
	1999	5	+ + +	10.4 ± 2.2	1–5	75–100	165.0 ± 4.4	12.0 ± 1.7	22.0 ± 1.6	35.0 ± 0.8
	2000	5	+ + +	7.8 ± 6.2	1–5	50–75	169.3 ± 6.6	13.7 ± 5.6	14.2 ± 1.2	42.3 ± 3.8
	2001	5	+ − −	5.2 ± 2.4	1–5	25–50	165.7 ± 15.5	8.6 ± 2.0	26.4 ± 2.8	45.4 ± 1.9
Point Mouille SGA	1997	5				50–75	102.0 ± 9.1	6.6 ± 2.7	8.1 ± 1.8	16.6 ± 3.8
	1998	5	+ + +	14.2 ± 9.4	5–25	75–100	125.4 ± 7.4	17.9 ± 2.5	15.6 ± 3.6	17.3 ± 2.1
	1999	5	+ + +	55.2 ± 9.4	75–100	0	27.0 ± 0.0	0.0	0.0	0.0
	2000	5	+ + +	53.2 ± 7.8	50–75	0	25.0 ± 0.0	0.0	0.0	0.0
	2001	5	+ + −	8.8 ± 5.7	75–100	1–5	43.9 ± 3.9	0.0	0.0	0.0
Saginaw–Gratiot SGA	1997	5				1–5	56.0 ± 3.7	0.0	0.0	0.0
	1998	5	+ + +	0.4 ± 0.4	1–5	1–5	58.0 ± 3.4	0.0	0.2 ± 0.2	0.7 ± 0.6
	1999	5	+ + +	2.8 ± 2.0	1–5	1–5	133.4 ± 4.0	3.2 ± 0.4	23.9 ± 2.3	34.4 ± 1.7
	2000	5	+ + +	21.2 ± 8.2	1–5	1–5	39.4 ± 3.0	0.0	0.0	0.0
	2001	5	+ + −	47.0 ± 0.0	50–75	1–5	60.1 ± 0.0	0.0	0.0	0.0
Lake Lansing North	1997	5				50–75	213.8 ± 4.9	11.2 ± 1.4	36.2 ± 2.3	46.3 ± 4.2
	1998	5	+ − +	2.4 ± 2.4	1–5	75–100	199.4 ± 11.5	16.6 ± 2.8	24.4 ± 3.1	35.2 ± 9.8
	1999	5	− − −	0.0 ± 0.0	0	50–75	171.1 ± 12.4	9.5 ± 2.0	22.8 ± 3.0	29.9 ± 1.1
	2000	5	+ + −	4.0 ± 1.7	1–5	25–50	171.9 ± 7.9	11.4 ± 1.1	24.9 ± 2.6	34.8 ± 2.6
	2001	5	− − −	0.0	0	1–5	187.1 ± 16.0	6.8 ± 2.1	20.6 ± 4.2	37.7 ± 10.6
St. Johns Marsh SGA	1998	5	+ − +	12.2 ± 4.3	5–25					
	1999	5	+ + −	6.8 ± 1.9	1–5	25–50	128.7 ± 4.1	8.2 ± 1.1	15.4 ± 0.5	44.0 ± 1.5
	2000	5	+ + +	29.4 ± 6.1	1–5	25–50	132.0 ± 4.6	7.0 ± 1.2	1.8 ± 0.2	6.3 ± 6.3
	2001	5	+ − −	26.4 ± 3.2	1–5	25–50	95.8 ± 6.3	1.5 ± 0.3	1.2 ± 0.5	11.0 ± 4.6

Table 3 (*continued*)

Year released, release site[a]	Year	*N*	Spring evaluations: Life stages present, eggs, larvae, adults	Spring evaluations: Total number[b] *Galerucella* per m^2	Spring evaluations: Percent damage, range	Fall evaluations: Percent cover, range	Fall evaluations: Mean stem height (cm)	Inflorescence characteristics (mean ± SEM): Number/m^2	Inflorescence characteristics (mean ± SEM): Length of terminal (cm)	Inflorescence characteristics (mean ± SEM): Flower buds/5 cm of terminal
1998										
Holland 'Windmill Island'	1998	5				75–100	215.7 ± 2.4	14.5 ± 2.3	55.6 ± 3.5	34.2 ± 1.7
	1999	5	− + +	4.8 ± 2.9	5–25	5–25	206.0 ± 5.5	18.6 ± 2.8	34.6 ± 2.4	36.2 ± 1.5
	2000	5	+ + +	50.6 ± 15.0	1–5	25–50	169.2 ± 11.7	9.2 ± 2.4	16.1 ± 2.7	15.4 ± 4.2
	2001	5	+ + +	35.4 ± 4.8	1–5	1–5	156.9 ± 9.4	12.1 ± 2.5	20.9 ± 4.2	20.5 ± 3.1
Reeds Lake West	1999	5	+ − +	0.8 ± 0.4	1–5	5–25	183.9 ± 5.9	15.9 ± 2.1	27.3 ± 3.1	35.6 ± 2.2
	2000	5	+ + +	8.4 ± 2.6	1–5	5–25	142.0 ± 9.8	6.3 ± 0.5	6.5 ± 1.5	34.0 ± 8.3
	2001	5	+ + +	12.6 ± 3.2	1–5	25–50	149.2 ± 10.9	13.2 ± 2.2	22.8 ± 4.0	32.1 ± 4.4
Reeds Lake East	1999	5	+ − +	0.8 ± 0.5	1–5	25–50	228.6 ± 6.9	12.2 ± 0.6	33.9 ± 1.6	28.9 ± 0.9
	2000	5	+ + +	13.6 ± 3.3	1–5	25–50	202.2 ± 6.4	8.9 ± 1.0	22.7 ± 2.2	34.4 ± 2.7
	2001	5	+ + −	4.0 ± 2.2	1–5	25–50	188.4 ± 11.2	7.9 ± 1.0	28.1 ± 4.0	431.5 ± 6.8
South Lake	1998	5				25–50	171.1 ± 11.4	7.1 ± 1.4	33.9 ± 1.6	32.8 ± 2.2
	1999	5	+ + −	12.2 ± 2.3	5–25	25–50	126.7 ± 9.8	9.9 ± 1.9	12.4 ± 1.9	37.0 ± 3.8
	2000	5	+ + +	45.2 ± 9.6	1–5	25–50	136.0 ± 6.5	4.6 ± 1.2	8.1 ± 2.0	36.2 ± 2.2
	2001	5	+ + −	4.6 ± 2.0	1–5	5–25	117.8 ± 17.9	4.3 ± 0.6	10.9 ± 2.1	37.4 ± 5.4
Allegan 'Hopkins'	1999	5	+ + +	1.8 ± 0.8	1–5	5–25	113.8 ± 2.7	10.8 ± 1.8	25.5 ± 1.6	51.0 ± 3.9
	2000	5	+ + +	4.8 ± 1.4	1–5	50–75	123.4 ± 2.4	6.6 ± 0.5	24.6 ± 2.1	58.4 ± 7.1
	2001	5	+ + +	4.2 ± 0.9	1–5	25–50	120.9 ± 2.0	6.5 ± 1.5	26.9 ± 1.5	47.7 ± 3.5
Aral Road	1998	5				50–75	129.2 ± 6.5	4.4 ± 0.9	36.4 ± 4.0	40.4 ± 3.2
	1999	5	+ − +	0.4 ± 0.2	1–5	50–75	128.0 ± 4.3	4.4 ± 0.8	24.4 ± 2.9	38.6 ± 2.8
	2000	5	− − +	0.2 ± 0.2	1–5	25–50	127.0 ± 8.7	2.7 ± 0.8	18.3 ± 1.9	29.4 ± 2.7
	2001	5	+ + −	4.0 ± 2.3	1–5	5–25	113.3 ± 9.0	3.3 ± 0.5	17.3 ± 2.9	30.11 ± 3.6
1999										
Millpond	1999	5				5–25	226.2 ± 8.2	9.5 ± 1.1	25.7 ± 2.2	42.3 ± 1.8
	2000	5	+ − +	13.6 ± 1.7	1–5	5–25	185.1 ± 9.3	4.4 ± 1.9	4.6 ± 1.8	34.6 ± 6.4
	2001	5	+ + +	18.8 ± 4.2	1–5	25–50	199.1 ± 6.2	10.0 ± 1.6	14.0 ± 2.0	33.2 ± 5.8
Kalamazoo River	1999	5				25–50	172.2 ± 9.9	8.2 ± 1.0	30.7 ± 0.6	36.8 ± 1.9
	2000	5	+ + −	13.0 ± 3.6	1–5	5–25	166.4 ± 9.4	6.5 ± 1.5	21.7 ± 1.2	38.0 ± 3.3
	2001	5	+ + +	9.0 ± 2.8	1–5	25–50	169.9 ± 7.7	8.3 ± 2.1	32.1 ± 3.2	48.5 ± 4.0
Boat Launch	1999	5				50–75	220.1 ± 2.5	13.8 ± 1.2	43.7 ± 4.2	49.1 ± 1.6
	2000	5	+ + +	17.4 ± 4.8	1–5	50–75	200.0 ± 7.5	10.7 ± 2.7	17.0 ± 1.5	40.8 ± 0.9
	2001	5	+ + −	22.0 ± 1.0	1–5	75–100	225.0 ± 5.2	11.8 ± 1.6	44.6 ± 4.6	57.5 ± 4.8

Table 3 (*continued*)

Year released, release site[a]	Year	*N*	Spring evaluations			Fall evaluations				
			Life stages present, eggs, larvae, adults	Total number[b] *Galerucella* per m^2	Percent damage, range	Percent cover, range	Mean stem height (cm)	Inflorescence characteristics (mean ± SEM)		
								Number/m^2	Length of terminal (cm)	Flower buds/5 cm of terminal
Riverside Park	1999	5				25–50	200.2 ± 7.3	19.0 ± 5.3	42.4 ± 2.1	33.2 ± 2.4
	2000	5	+ + +	0.8 ± 0.4	1–5	50–75	165.2 ± 7.8	4.8 ± 1.2	8.4 ± 1.7	37.3 ± 3.4
	2001	5	– – –	0.0	0	25–50	151.3 ± 5.8	5.8 ± 2.2	12.1 ± 3.5	22.3 ± 7.4
KBS	1999	5				25–50	172.2 ± 6.1	9.0 ± 1.3	30.8 ± 2.3	28.3 ± 1.4
	2000	5	+ + –	5.4 ± 2.3	1–5	25–50	172.2 ± 6.1	9.0 ± 1.3	30.1 ± 2.2	28.1 ± 1.3
	2001	5	+ + –	5.4 ± 1.7	1–5	50–75	172.6 ± 7.4	8.5 ± 1.6	33.7 ± 6.0	32.0 ± 2.8

[a] SGA, State Game Area; SRA, State Recreation Area; WA, Wildlife Area.
[b] Egg masses + larvae + adults.

while others such as Waterloo have declining *Galerucella* numbers, and *L. salicaria* appears to be recovering. At this early stage following release (1–4 years) the majority of sites do not show clear impacts that could be reliably discerned from normal *L. salicaria* seasonal variability.

In contrast, significant impacts on *L. salicaria* morphology and on associated plant communities were present at all 1994 release sites. At Nayanquing Point 'Field' release location, *L. salicaria* stem number increased significantly, and stem height decreased significantly in both 2000 and 2001 in contrast to 1995 (Table 4). Percent cover was significantly reduced in 2000 but not 2001 and nontarget species richness, while not significantly affected in 2000 was significantly increased in 2001 (Table 4). At Nayanquing Point 'Marsh' release, *L. salicaria* stem number remained the same, while percent cover and stem height decreased significantly, and nontarget species richness was significantly increased in both 2000 and 2001. The Nayanquing Point 'Control' site, showed no statistically significant changes in vegetation characteristics from 1995 to 2000; however *L. salicaria* stem number, percent cover, and stem height all showed large numerical increases from previously low levels. By 2000, all 1994 control sites have been colonized by *G. calmariensis* and showed varying impacts depending on when colonization occurred.

At both the Crow Island 'Road' and 'Meadow' release locations, *L. salicaria* stem number was unchanged, while stem height decreased significantly, and nontarget species richness increased significantly in both 2000 and 2001 (Table 4). Percent cover of *L. salicaria* declined significantly at both sites with the exception of the Meadow site in 2001. The Crow Island 'Control' site had a significant decrease in *L. salicaria* stem height in 2000. While average stem height declined further in 2001 the difference was not significant due to increased variability.

Stem height of *L. salicaria* significantly decreased, and nontarget species richness significantly increased from 1995 to 2000 at the Shiawassee River 'Cage' release location with no significant changes in number of stems or stem height (Table 4). At the Shiawassee River 'Control' location, stem height decreased significantly in both 2000 and 2001. In addition nontarget species richness decreased at this site from the 1995 levels.

4. Discussion

Galerucella beetles established at 100% of the 24 release locations monitored in these studies and have persisted for 3–7 years. Several sites, such as Lake Lansing North, Lost Nations 'Rifle Range,' and Grand River 'Riverside Park,' have maintained very low populations of beetles for several years. While *Galerucella* populations at these sites appear tenuous, we have ob-

Table 4
Impact of *Galerucella* releases on mean number of *L. salicaria* mature stems, percent cover, stem height, and number of nontarget species in three locations in Michigan

Location	Year	*N*	Mean + SEM[a]			
			Number of stems	Percent cover	Stem height	Nontarget species richness
Nayanquing Point 'Field'	1995	10	12.9 ± 4.3	31.0 ± 7.1	111.0 ± 5.4	3.4 ± 0.3
	2000	10	40.1 ± 9.7*	12.1 ± 4.0*	21.9 ± 2.0***	5.4 ± 0.9 ns
	2001	10	34.7 ± 9.6*	19.2 ± 4.9 ns	75.1 ± 7.1***	5.0 ± 0.4**
Nayanquing Point 'Marsh'	1995	8	18.0 ± 3.8	39.8 ± 8.2	112.9 ± 9.8	2.0 ± 0.3
	2000	8	10.4 ± 3.5 ns	3.2 ± 1.2**	30.1 ± 4.8***	5.6 ± 0.9**
	2001	8	13.5 ± 3.1 ns	15.3 ± 3.9*	72.2 ± 8.0**	8.4 ± 0.6***
Nayanquing Point 'Control'	1995	3	0.1 ± 0.1	0.3 ± 0.3	90.0 ± 90.0	5.0 ± 1.2
	2000	3	40.0 ± 23.4 ns	36.8 ± 25.1 ns	89.2 ± 34.8 ns	6.7 ± 1.2 ns
	2001	3	17.3 ± 6.2 ns	1.3 ± 0.3 ns	78.5 ± 22.3 ns	6.0 ± 1.5 ns
Crow Island 'Road'	1995	9	18.3 ± 6.2	31.4 ± 7.2	105.8 ± 7.8	3.6 ± 0.6
	2000	9	17.0 ± 4.7 ns	4.3 ± 2.7**	49.9 ± 10.0***	10.6 ± 1.1***
	2001	9	18.0 ± 5.5 ns	6.1 ± 3.0**	66.4 ± 10.2***	10.9 ± 1.1***
Crow Island 'Meadow'	1995	10	12.6 ± 5.8	20.0 ± 8.0	103.0 ± 8.4	3.6 ± 0.5
	2000	10	11.7 ± 7.3 ns	1.0 ± 0.4*	20.1 ± 12.4***	7.5 ± 0.6***
	2001	10	15.0 ± 11.3 ns	4.6 ± 3.9 ns	26.3 ± 9.0***	6.8 ± 1.0*
Crow Island 'Control'	1995	3	6.8 ± 4.1	31.7 ± 7.5	136.7 ± 3.3	4.3 ± 1.5
	2000	3	34.7 ± 33.7 ns	13.5 ± 13.2 ns	54.0 ± 21.5*	5.0 ± 1.0 ns
	2001	3	12.0 ± 11.5 ns	3.5 ± 3.3*	45.8 ± 28.8 ns	5.3 ± 0.3 ns
Shiawassee River 'Cage'	1995	6	14.0 ± 4.5	33.3 ± 8.7	118.3 ± 23.6	1.3 ± 0.4
	2000	6	27.2 ± 15.0 ns	12.6 ± 7.9 ns	36.9 ± 10.1**	4.7 ± 0.5***
	2001	6	14.5 ± 9.5 ns	10.9 ± 9.0 ns	52.4 ± 8.7*	5.5 ± 0.7***
Shiawassee River 'Control'	1995	3	10.1 ± 6.1	31.3 ± 15.2	126.7 ± 3.3	2.7 ± 0.3
	2000	3	39.3 ± 9.8 ns	24.0 ± 7.8 ns	77.6 ± 16.1*	2.0 ± 0.0 ns
	2001	3	26.0 ± 9.5 ns	6.7 ± 1.7 ns	47.3 ± 3.5***	1.3 ± 0.3*

[a] Means from 1995 versus 2000 and 1995 versus 2001 were contrasted with *t* tests. Means followed by an * are significantly different from 1995 at $P \leqslant 0.05$, $^{**}P \leqslant 0.01$, $^{***}P \leqslant 0.001$, ns, no significant difference.

served populations at some sites to rebound from similarly low levels. For example, at Saginaw–Gratiot SGA only two *Galerucella* were found in the quadrats in 1998 but the population reached 21.2 per m^2 two years later. We hypothesize that in such cases increased densities of *Galerucella* may occur outside of our predefined sample areas, and thus yield very low counts until populations begin to increase at the site in general. Blossey and Skinner (2000) reported a similar observation.

Similar to prior reports, all three of the 1994 releases produced large populations of *Galerucella* within a 4–5 year timeframe (Blossey and Skinner, 2000). We observed that at two sites with multiple releases (Crow Island and Nayanquing Point), one release established and expanded (Crow Island 'Road' and Nayanquing Point 'Marsh') while the other never generated large *Galerucella* numbers until it was eventually overtaken by the population of the adjacent release. In both cases, the drier of the two sites failed to initially establish large populations. This may be a coincidence, or alternatively may be related to differences in predation (Nechols et al., 1996; Sebolt, 2000; Sebolt and Landis, 2002) or other factors that varied from site to site. The aggregation behavior of *Galerucella* spp. may also play a part. Grevstad and Herzig (1997) showed that marked *G. calmariensis* found *L. salicaria* patches from distances up to 847 m away (maximum tested) and then aggregated in local areas where conspecifics occur. It may be that the wetter sites experienced an early population advantage, perhaps due to reduced predation, and subsequently attracted individuals from the nearby sites.

Of the 19 sites monitored for 1–4 years (i.e., 1997–1999 releases), three generated *Galerucella* populations that caused severe damage to *L. salicaria*. At Saginaw–Gratiot SGA, *Galerucella* damage completely prevented flowering of *L. salicaria* within a 200 m radius of the release site in 2000–2001. At Pointe Mouillee, *L. salicaria* was absent in 2000 from seven of the nine quadrats originally sampled in 1997, and the average number of stems had fallen from 35.8 to 0.3 per m^2, a reduction of over 98%. *L. salicaria* rebounded somewhat in 2001 but was still absent from four of nine quadrats.

Galerucella impact on vegetation characteristics is a dynamic process. Releases of *Galerucella* initially have very slight impacts on *L. salicaria* and nontarget species until the population becomes well established. We have observed impacts on *L. salicaria* height and flowering as early as the year following release (Pointe Mouillee), however, this appears to be the exception. In general, 3–5 years are required until *Galerucella* populations cause consistent reductions in plant height or flowering. In addition to the time element, there is a spatial aspect as well. As *Galerucella* populations deplete the *L. salicaria* in the area of initial population buildup, they disperse with peak density occurring in a moving wave over time (Blossey and Skinner, 2000, Landis personal observation). This is best understood in the context of *Galerucella* life history.

Adult *Galerucella* emerging in spring from localized aggregations on individual *L. salicaria* plants (Grevstad and Herzig, 1997). Beetles move frequently and over time oviposition occurs on most plants in a localized area. Early-instar larval feeding in the shoot tips of these plants destroys the apical meristems and results in stunted plants and a delay or prevention of flowering. Later instars defoliate leaves and stems. In the first year(s) after release, we frequently observed areas where *Galerucella* damage resulted in localized patches of stunted or defoliated plants in a larger expanse of healthy *L. salicaria*. During *L. salicaria* flowering in July, this appears as a patch of green in a stand of purple flowering plants. In subsequent years, these stunted or defoliated areas generally enlarge. Within 3–5 years, *Galerucella* larval populations may reach the point where they will defoliate most of the *L. salicaria* in a local area. We have observed areas as large as 260 ha with no live loosestrife foliage in late June at the end of the larval feeding period (Shiawassee River). The larvae responsible for this defoliation pupate nearby and the adults that subsequently emerge have no live *L. salicaria* foliage to feed on. The teneral adults must disperse from such heavily defoliated areas to find *L. salicaria* foliage. This results in the *Galerucella* infested area expanding over time but may also allow a rebound in *L. salicaria* density and height in the original release area. This appears to be occurring at the Nayanquing Marsh and Shiawassee River sites in 2001.

At the plant-level, increasing *Galerucella* populations result in a sequence of impacts. Low populations of *Galerucella* result in adult feeding during spring and later larval damage to the growing tips. Impacts include a reduction in plant height and a delay in flowering. Apical meristems damaged by larval feeding typically will not flower, however, the lateral buds that subsequently break often produce flowers. These inflorescences are typically smaller than those on undamaged plants and bloom much later. As *Galerucella* populations increase, all plant meristems are damaged by early-instar feeding and stems seldom exceed 1 m in height (Tables 3 and 4). Second and third instar larvae defoliate the leaves and stem tissue that results in desiccation of the shoots. Following desiccation of its spring growth, *L. salicaria* plants often reshoot stems from the crown (Katovich et al., 1999) and in some situations, regrowth may produce flowers late in the summer. Alternatively, we have observed that newly emerged adults often feed heavily and may also oviposit (F_2 generation) on the regrowth. Combined adult and larval feeding on regrowth can result in a second defoliation of a plant in a single season. Katovich et al. (1999) reported that in excess of two years of *Galerucella* defoliation would be required to cause plant mortality. In cases where a second generation fed on *L. salicaria* regrowth, we have observed *L. salicaria* root crown death after two consecutive years of such damage (Nayanquing Point Marsh). Defoliation and subsequent regrowth can result in an increase in *L. salicaria* stem density (Blossey and Skinner, 2000), however, stem height and percent cover are often simultaneously reduced (Table 4).

Additional studies will be required to measure the full impacts of biological control of *L. salicaria* on associated plant communities. Our observations indicate that richness of nontarget plant species generally increases as *L. salicaria* percent cover and height decline. While the dominant species (percent cover in 2000–2001) that recolonized sites were generally present in 1995 samples, we also observed species recruitment as *L. salicaria* density declined. This is at odds with the findings of Farnsworth and Ellis (2001) that indicate that species richness was not correlated with *L. salicaria* density within a year. It may be that our sites differ from theirs in characteristics that affect plant recruitment or that the 5 years which transpired between plant community sampling in our study may have allowed time for species richness differences to emerge.

In conclusion, *G. calmariensis* is widely established in Michigan and causes significant local suppression of *L. salicaria*. While *G. pusilla* was reportedly released in at least five sites in 1994, it has not been detected in follow-up evaluations. *G. calmariensis* populations typically require ca. 3–5 years to produce major impacts on *L. salicaria* although significant impacts have been observed earlier in at least one case. Our observations indicate that *G. calmariensis* populations are slower to develop in sites that have little or no standing water for much of the season. We speculate that increased predation may limit establishment or slow population growth in such sites. Our plant community studies conducted 6–7 years after initial release indicate significant reductions in *L. salicaria* height and percent cover while stem density is generally unchanged. Richness of nontarget plant species has significantly increased at all five 1994 release sites while remaining equal or in one case declining significantly at one control site. The initial successes of these natural enemies in impacting *L. salicaria* indicate the need for additional studies on habitat restoration to assure a return of desirable wetland community structure and function.

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