

Impact of the biological control agent *Rhinoncomimus latipes* (Coleoptera: Curculionidae) on mile-a-minute weed, *Persicaria perfoliata*, in field cages

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Abstract

A host-specific Asian weevil, *Rhinoncomimus latipes* Korotyaev, was approved in 2004 for release in North America for control of mile-a-minute weed, *Persicaria perfoliata* (L.) H. Gross (formerly *Polygonum perfoliatum* L.), an invasive annual vine from Asia. The impact of *R. latipes* feeding on *P. perfoliata* was studied in field cages over a 2-year period. In 2006, 20 weevils introduced into cages with single plants in May (when weevils first emerge from overwintering) suppressed seed production for about 9 weeks, while weevils introduced in June (when the first summer generation of adults emerge) did not affect seed phenology. Plants in all cages produced substantial numbers of seeds late in the year, but the average seed (achene) weight was reduced for plants with 20 weevils per plant introduced in May. In 2007, plants grown with some competition from other plants within field cages showed substantial mortality, with 63% of plants with 10 or 20 weevils and 75% of plants with 40 weevils per plant dead by mid-August, compared with 12.5% of control plants. Reproduction was delayed by more than a month in surviving plants with 10 or 20 weevils, and by more than 2 months in the few survivors with 40 weevils. Surviving plants with 40 weevils per plant showed loss of apical dominance, which can allow plants to compensate for herbivore damage, but in the case of a light-adapted vine like *P. perfoliata* may prevent the plants from achieving needed sun exposure. These results suggest that *R. latipes* feeding on *P. perfoliata* has the potential to impact plant growth and reproduction, and can put affected plants at a substantial competitive disadvantage.

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Keywords: *Polygonum perfoliatum*; *Persicaria perfoliata*; *Rhinoncomimus latipes*; Biological control weeds

1. Introduction

Mile-a-minute weed, *Persicaria perfoliata* (L.) H. Gross (formerly *Polygonum perfoliatum* L.) is an annual vine from Asia that infests natural areas in a variety of habitats in its imported range. It has developed extensive monocultures, especially in disturbed open areas throughout the Mid-Atlantic region of the United States. The North American population is thought to have originated near York, PA, in the 1930s, probably introduced as a seed contaminant with holly seed imported from Japan (Moul, 1948). The

plant can now be found from Delaware west to Ohio, south to West Virginia and north to Massachusetts.

Persicaria perfoliata produces terminal clusters of about 10–20 achenes (one-seeded fruits), covered by perianths that turn blue as they mature. Fruits may be consumed by birds, deer, and other mammals, and this can contribute to seed dispersal (Okay, 1997; personal observation). If they are not consumed they fall to the ground where the perianth disintegrates, leaving the shiny black pericarp exposed. Seeds are also dispersed by water (McCormick and Hartwig, 1995; Mountain, 1989). Pollination is not required for seed set (Okay, 1997), although bumble bees will visit the small inconspicuous flowers (personal observation). *Persicaria perfoliata* seed dormancy is enforced

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by both coat-imposed and chemical-based mechanisms (Colpetzer and Hough-Goldstein, 2004), with a period of cold-wet stratification required for germination.

A biological control program was initiated by the USDA Forest Service in 1996 (Wu et al., 2002). More than 100 insect species were identified on *P. perfoliata* in China, including several that appeared to have a narrow host-range (Ding et al., 2004). One of these, *Rhinoncomimus latipes* Korotyaev (Coleoptera: Curculionidae), was tested on plant species in China and in quarantine in Delaware, and found to be extremely host-specific (Colpetzer et al., 2004a; Price et al., 2003). This small weevil (~2 mm long) was approved for release in the United States by USDA-APHIS in 2004.

Eggs of *R. latipes* are laid on mile-a-minute leaves and stems and hatch in about 5 days. Neonates crawl along stems and enter a node, where they feed internally for 1–2 weeks, after which they drop out of the stem and pupate in the soil. Adults emerge about 1 week later and feed on mile-a-minute leaves and terminals (Colpetzer et al., 2004b; Price et al., 2003). Larval feeding produces characteristic damage at the nodes, ranging from discolored scars to obvious holes with frass present. In the field, overwintered adults emerge in early spring and complete three to four overlapping generations until early to mid-September, when egg laying ceases (Lake, 2007). Adult weevils overwinter in the soil or leaf litter (personal communication, Fu Weidong, Chinese Academy of Agricultural Sciences, Beijing).

Rhinoncomimus latipes have been reared at the New Jersey Department of Agriculture Phillip Alampi Beneficial Insect Laboratory in Trenton, NJ, since fall of 2004. By the end of 2007 more than 60,000 weevils had been reared and released, mostly in New Jersey, but also at sites in Delaware, Pennsylvania, West Virginia, and Maryland. Although it is too soon to assess their impact in the field, weevil populations have established at nearly every release site, and weevils have heavily defoliated mile-a-minute plants in some areas (Lake, 2007; personal communication, Mark Mayer, NJ Department Agriculture).

Biological control workers increasingly emphasize the need for quantitative evaluation of agent efficacy in reducing plant populations (Myers and Bazely, 2003). While insect establishment and feeding may result in weed control, in some cases plants are able to compensate or even over-compensate for herbivory, depending on biotic and abiotic conditions and timing and intensity of feeding (Hawkes and Sullivan, 2001; Maschinski and Whitham, 1989; Trumble et al., 1993; Wise and Abrahamson, 2005). Although effects of insect feeding on single plants do not necessarily translate into population-level effects, McClay and Balciunas (2005) point out that without damage at the individual plant level an agent cannot have a population-level effect, and therefore it is important to understand per-capita effects.

To gain a better understanding of the impact of *R. latipes* feeding on *P. perfoliata*, experiments were conducted in 2006 and 2007 using single mile-a-minute plants enclosed in weevil-proof cages with various numbers of weevils applied

at different times. In a preliminary study in 2005, isolated *P. perfoliata* plants in field cages were shown to be highly plastic in response to light, producing more than 2200 seeds per plant in full sun but fewer than 400 in the shade (Hough-Goldstein, in press). Therefore in the experiments reported here all treatments were blocked by location with similar sun exposure. In 2006 we assessed the impact of two levels of weevil numbers added to isolated plants early or later in the season, with treatments timed to coincide with emergence of adults from overwintering (“early” treatments), or with the emergence of the first summer generation of new weevils (“late” treatments; Lake, 2007; Price et al., 2003). In 2007 we tested the impact of three levels of weevils under conditions more closely approximating the field situation, with some additional plant growth in the cages surrounding a single mile-a-minute plant.

2. Materials and methods

2.1. 2006 Experiment

Thirty cages were placed over single *P. perfoliata* plants growing naturally in the field at a site in White Clay Creek State Park near Newark, DE (latitude 39.44°, longitude 75.45°, elevation 31 m) on 19 May 2006, when mile-a-minute plants were about 30 cm tall. Field cages were approximately 2 m tall and 0.9 m square. They were made of white polyester netting material with a mesh of approximately $10 \times 8/\text{cm}^2$ (BioQuip Products, Inc., Gardena, CA), with a Velcro opening sewn into the length of one side, and supported by frames constructed of 1.9 cm diameter PVC conduit pipe. Cages were open at the bottom, and fabric edges were buried in the soil. The cages were arrayed along the edge of a meadow in a randomized complete block design, so that plants in the same block were growing near each other and had similar exposure to sun, with most plants exposed to full sun for much of the day. Plants other than the focal mile-a-minute plant were pulled or cut off at the base when cages were installed, and removed as needed during the season. Each *P. perfoliata* plant was provided with a tomato cage extended with three bamboo poles wrapped in wire, to support growth of the vine.

There were six replicate cages each of five treatments: Early High, 20 weevils per cage added on 26 May; Early Low, 5 weevils per cage added on 26 May; Late High, 20 weevils per cage added on 23 June; Late Low, 5 weevils per cage added on 23 June; and Control, no weevils added. Weevils were obtained from the Phillip Alampi Beneficial Insect Laboratory, Trenton, NJ, and were assigned randomly to the different treatments. Although they were not sexed, weevil populations checked during routine rearing generally had a 1:1 sex ratio (personal communication, Daniel Palmer, NJ Department Agriculture).

Cages were checked weekly for estimated percent defoliation, number of weevils that could be observed, and presence of achene clusters on plants. Nylon window screening was placed in the bottom of each cage, and achenes were

collected from the screen each week beginning in late July, returned to the laboratory and counted. During the last 3 weeks of seed collection (25 October through 10 November) single aliquots of achenes from each treatment and replicate were removed as the seeds were counted, cleaned of all remnants of perianths by hand, and then counted and weighed in a group. Most aliquots consisted of about 100 achenes, but if fewer than 100 were available, all achenes were used as long as at least 20 were present. Total weights were divided by the number of achenes weighed to give an average weight per achene for that date, treatment, and replicate. Plants were cut at the soil surface on 15 November and the stem circumference at the base was measured using a tape measure. Plants were then left to dry in paper bags in a greenhouse for several weeks, after which they were weighed.

2.2. 2007 Experiment

On 8 May 2007, 48 cages identical to those used in 2006 were installed at the Burrow's Run site at the Ashland Nature Center in Hockessin, DE (latitude 39.48°N, longitude 75.38°W, elevation 80 m), with each cage again enclosing a single mile-a-minute plant. Cages were placed over plants growing in the field, and if necessary other mile-a-minute plants were pulled or cut at the base, leaving a single plant. However, in 2007 other plant species growing in each cage were left intact, except that any plants taller than ~30 cm were cut to that height using pruning shears.

As in 2006, treatments were assigned using a randomized complete block design, with plants in the same block growing near each other and with similar sun exposure. Twelve replicate cages each were assigned to four treatments in 2007: control (no weevils); 10 weevils per plant; 20 weevils per plant; and 40 weevils per plant. Weevils were sent from the Trenton laboratory pre-counted and sexed (approximately half male and half female for each treatment), and were placed in the cages on 16 May 2007. Cages were subsequently checked once per week for mile-a-minute plant mortality, height (16 May through 22 June only), estimated percent defoliation, and presence of flower buds and developing achenes. Other plants growing in the cages around the focal mile-a-minute plant were trimmed to ~30 cm each week as needed. The percent cover of other plants in each cage was estimated on 16 May and 7 June.

Three destructive samples of four randomly selected blocks (four plants from each of the four treatments) were planned at 6-week intervals, to be conducted on approximately 22 June, 7 August, and 18 September. The first sample was taken as planned, but consisted of four control and 10-weevil plants, but only three 20-weevil plants and two 40-weevil plants because of plant mortality in these treatments. Because plant mortality continued to reduce the available sample size, the last two samples were combined and collected on 20 August.

For each sample, a large plastic bag was placed over the entire mile-a-minute plant in each cage, and the plant was

cut off at soil level. The bag was then returned to the laboratory, and the number of weevils, total number of nodes, damaged nodes, stem terminals, and number of terminals with buds, immature, and mature achene clusters were counted. Plants were then dried and weighed as in 2006. A small potted mile-a-minute plant was placed in each cage to collect any additional weevils that may have fallen off during the initial collection. These were collected in plastic bags 2–3 days after the initial sample, and any additional weevils were counted and added to the initial counts.

2.3. Statistical analysis

Data were transformed by square-root ($x + 0.5$) to reduced heteroskedasticity of variance residuals. Transformed data were analyzed using two-way ANOVA, by treatment and block. Tukey's test was used for mean separation. In addition, for achene weights in 2006, Dunnett's test at $\alpha = 0.05$ was used to compare weights from each weevil treatment to those produced by the control plants. All analyses were conducted using SAS/STAT[®] 9.1.3 software (SAS Institute Inc., 2002–2004). Nontransformed means and standard errors are presented in tables and figures.

3. Results

3.1. 2006 Experiment

Two caged plants died early in the experiment, and were excluded from analyses. Weevils reproduced in the cages, with numbers counted exceeding the numbers originally added in the Early Low and Early High cages (5 or 20 weevils added on 26 May) by mid-July. Numbers also increased in the Late Low and Late High treatments (added on 23 June), but accurate weevil counts were difficult from mid-July on due to the size and density of the plants.

The Early High plants produced very few achenes during the first 9 weeks that achenes were collected (24 July–17 September), compared with 300–400 achenes per plant for the Control plants and the Late Low treatments ($F_{4,18} = 3.77$, $P = 0.0213$, Fig. 1A). However, all treatments began to produce large numbers of achenes during October, and differences by treatment were not significant for total numbers of achenes ($F_{4,18} = 1.03$, $P = 0.4175$; Fig. 1B) or plant dry weights ($F_{4,18} = 0.18$, $P = 0.9455$). The stem circumferences of *P. perfoliata* plants in the cages averaged 2.6–4.2 cm at the base of stems at the time of harvest, with no significant differences by treatment (Table 1).

Average achene weights differed by treatment ($F_{4,18} = 4.53$, $P = 0.0028$; Table 1), with achenes produced in the Late Low cages significantly heavier than those produced in the Early High cages. According to Dunnett's test, the Early High treatment achenes were significantly lighter than those produced in the Control cages, and were the only ones to differ from the Control achenes.

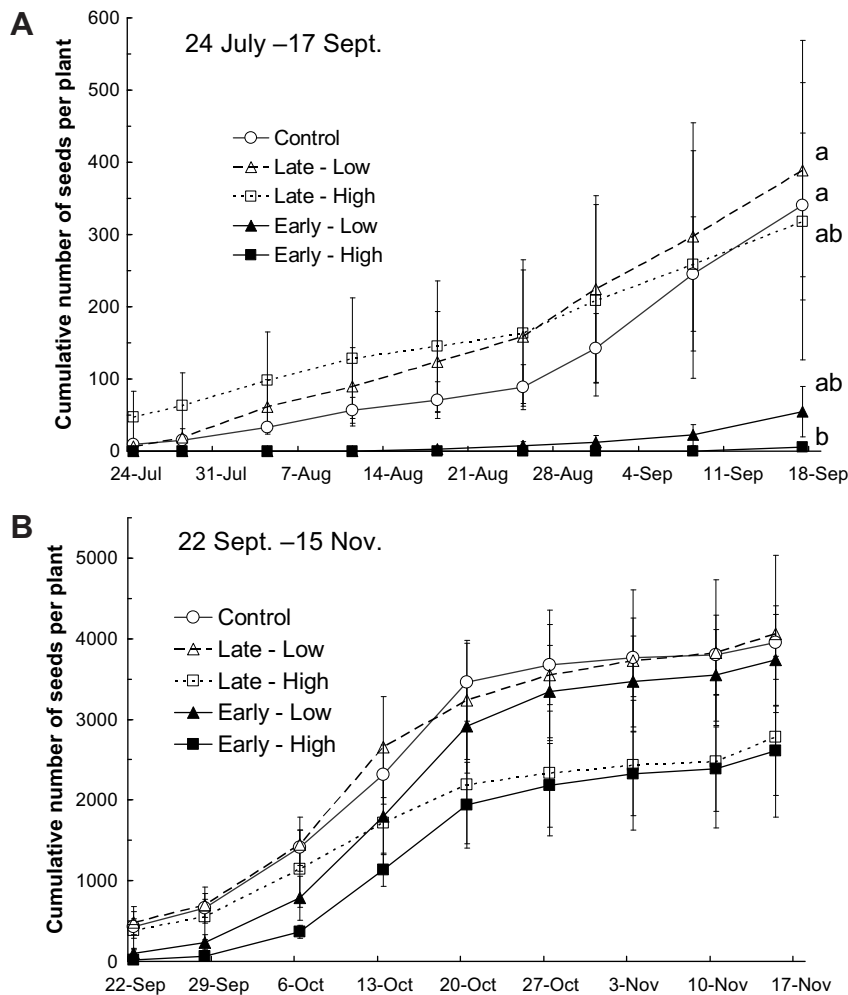


Fig. 1. Effect of weevil treatments on cumulative total number of seeds (achenes) produced (means \pm SE) during (A) the first 9 weeks, and (B) the last 9 weeks of seed collection, for single *Persicaria perfoliata* plants enclosed in cages in 2006. Means with the same letter are not significantly different (Tukey's test on square-root transformed data; untransformed means and standard errors are shown). "Late" treatments had weevils added on 23 June, and "Early" weevils were added on 26 May; "Low" treatments received 5 weevils, and "High" treatments received 20 weevils per cage.

Table 1

Effect of weevil treatments on stem circumference at harvest and on individual achene weights (means \pm SE) for aliquots of achenes collected from *Persicaria perfoliata* plants enclosed in cages in 2006

Treatment	Stem circumference		Achene weight	
	n	(cm)	n	(mg)
Late Low	6	2.9 \pm 0.2	16	19.9 \pm 0.2a
Control	5	3.9 \pm 0.9	13	19.3 \pm 0.3ab
Early Low	5	2.6 \pm 0.2	14	19.1 \pm 0.4ab
Late High	6	4.2 \pm 1.0	12	18.7 \pm 0.2ab
Early High	6	2.6 \pm 0.2	17	18.1 \pm 0.4b*

Means followed by the same letter are not significantly different ($P > 0.05$, Tukey test).

"Late" treatments had weevils added on 23 June, and "Early" weevils were added on 26 May; "Low" treatments received 5 weevils, and "High" received 20 weevils per cage.

* Significantly different from Control ($P < 0.05$, Dunnett's test).

3.2. 2007 Experiment

In 2007, competing vegetation within the cages (cut back weekly to \sim 30 cm in height) covered approximately 40–

60% of the soil surface in the cages on 16 May, when weevils were added to the cages, and 80–85% of the soil surface in cages by early June. Mile-a-minute plants in the cages were 12–19 cm tall on 16 May, and $>$ 30 cm tall in all treatments by 30 May. Plant heights were difficult to measure accurately by mid-June, as the vines grew over their supports and flopped down.

Plants exposed to 10, 20, or 40 weevils in 2007 showed substantial mortality compared to controls, beginning 2 weeks after weevils were added (Fig. 2). By 6 weeks after treatment, 25% of the plants with 10 weevils, 50% of plants with 20 weevils and 58.3% of those with 40 weevils were dead, while none of the control plants had died. Following the first destructive sample, mortality continued to occur (Fig. 2) so that by mid-August 62.5% of the remaining plants with 10 or 20 weevils and 75% of those with 40 weevils were dead, compared with only 12.5% of the control plants.

Flower buds and immature achenes were observed on control plants beginning on 15 June, while plants with 10

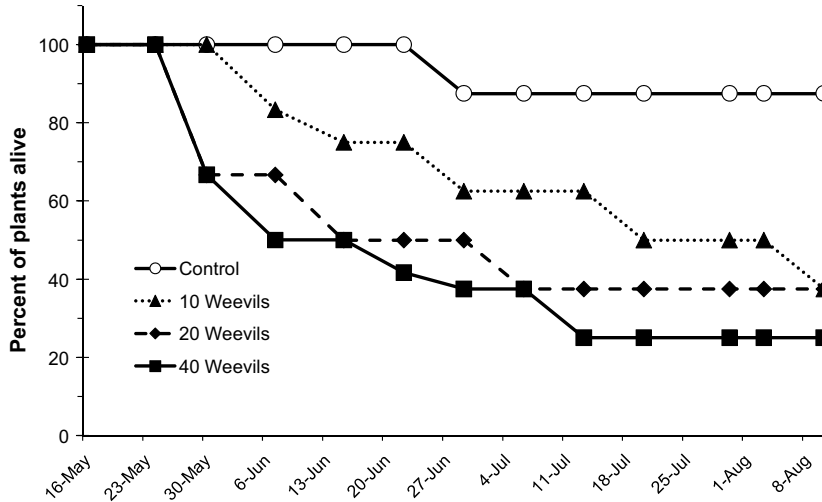


Fig. 2. Survival of individual plants exposed to 0 (Control), 10, 20, or 40 weevils in field cages in 2007 (100% alive = 12 plants from 16 May–22 June and 8 plants from 29 June–10 August).

or 20 weevils did not produce any flower buds or achenes until 20 July. The few remaining live plants with 40 weevils did not produce any flowers or achenes before the final destructive sample on 20 August.

In the first destructive sample of plants from four randomly chosen blocks, the two surviving plants with 40 weevils per plant had about eight times as many terminals and about six times as many nodes and damaged nodes as those from any other treatment (Table 2). The dry weight of the two surviving 40-weevil plants was also higher than that of the 10-weevil plants. An average of about 30 weevils per plant were collected from the plants that had received 40 weevils, while an average of 4.7 and 1.3 weevils per plant were collected on the 20 and 10-weevil plants, respectively (Table 2). No flower buds or achenes were found on any of the plants from weevil treatments, while control plants had an average of 4.5 ± 1.8 terminals with buds or immature achene clusters on 22 June. By 20 August, when the second destructive sample was taken, the surviving mile-a-minute plants varied greatly in size in all treatments, and there were no significant differences in any of the parameters measured (Table 2).

4. Discussion

In 2006, *P. perfoliata* reproduction was almost completely suppressed between late July and mid-September in plants with early (May) addition of weevils at the high level (20 weevils per plant). However, all plants produced numerous achenes in October, resulting in no significant difference by treatment in total seed production over the season. Seed quality did appear to be reduced, as the average weight of achenes in the Early High treatments was 6% lower than that of the controls. Seed size generally impacts germination and seedling establishment (Sultan, 2001, and references therein) and thus reduction in achene weight likely represents a fitness cost to the plant. In this experiment virtually all of the caged plants were unusually large and robust, probably because all plants within the cages around the central mile-a-minute plant had been removed, and removal of competing vegetation continued throughout the summer. Stem circumferences of plants in the cages averaged 2.6–4.2 cm at the base, while plants growing under crowded conditions in virtual monocultures outside of the cages had much thinner stems. The unusually robust

Table 2

Plant characteristics and weevils (means \pm SE) counted in first (22 June) and second (20 August) destructive sample of surviving *Persicaria perfoliata* plants enclosed in cages in 2007

Treatment	n	No. terminals	No. nodes	No. damaged nodes	Plant dry wt. (g)	No. weevils
<i>22 June</i>						
40 weevils	2	159 \pm 125a	1241 \pm 731a	414 \pm 231a	75.3 \pm 50.3a	30.0 \pm 5.0a
20 weevils	3	24 \pm 6b	214 \pm 76b	71 \pm 39b	16.3 \pm 10.4ab	4.7 \pm 0.7b
10 weevils	4	19 \pm 14b	162 \pm 117b	29 \pm 21b	6.1 \pm 5.3b	1.3 \pm 0.9bc
Control	4	28 \pm 17b	177 \pm 92b	0 \pm 0b	16.6 \pm 7.6ab	0.0 \pm 0.0c
<i>20 August</i>						
40 weevils	2	41 \pm 23	733 \pm 682	261 \pm 234	22.2 \pm 18.8	13.0 \pm 12.0
20 weevils	3	153 \pm 78	1274 \pm 619	449 \pm 222	156.1 \pm 112.5	40.0 \pm 27.9
10 weevils	4	341 \pm 118	4452 \pm 1808	889 \pm 399	238.3 \pm 115.0	22.5 \pm 13.8
Control	7	233 \pm 105	3777 \pm 2021	0 \pm 0	191.0 \pm 74.3	0.0 \pm 0.0

Means within a column followed by the same letter are not significantly different ($P > 0.05$, Tukey test).

plants in the cages were probably also unusually capable of surviving and compensating for weevil damage by producing seeds before they were killed by frost in the fall.

In 2007, under conditions more closely approximating the field situation (i.e. with at least some competition from other plants within the cages), as few as 10 weevils per plant caused 63% mortality, and 40 weevils caused 75% mortality of *P. perfoliata*. Other studies comparing impacts of herbivory on plants have also shown that the impact can be much greater under stressed conditions (Maschinski and Whitham, 1989), although the opposite pattern has also been found (Hawkes and Sullivan, 2001).

The usual mechanism by which dicots have been shown to compensate or overcompensate for herbivory has been through release of apical dominance due to damage to the shoot apex, causing abundant growth of lateral branches, which may promote increased seed and/or biomass production (Benner, 1988; Irwin and Aarssen 1996a,b). In our study, the first destructive sample in 2007 showed clear loss of apical dominance in the surviving plants with 40 weevils per plant. These plants produced large numbers of small terminals and “stacked” nodes, close together on stems. This can be part of a compensatory response, in which a plant may produce more seeds (at the ends of the larger number of terminals). However, for a light-adapted vine such as *P. perfoliata* numerous short terminals may not allow the plant to achieve needed sun exposure when in competition with other plants. Irwin and Aarssen (1996a,b) argue that the benefits of apical dominance will be greatest where competition for light is most intense, and *P. perfoliata* is clearly adapted to compete for and respond to light (Hough-Goldstein, in press).

As in the 2006 “Early” treatments, feeding by *R. latipes* placed in cages in May of 2007 again caused a dramatic change in the phenology of seed production, with flowering and achene production delayed by more than a month in surviving plants with 10 or 20 weevils, and by more than 2 months in those with 40 weevils compared to control plants. This phenological shift could have a serious negative impact on seed production in years where an early frost curtails the season (Sultan, 2001, and references therein).

Trumble et al. (1993) emphasize the importance of timing of herbivory in determining whether plants are able to compensate, and our study supports the generalization that plants are less tolerant of damage early compared with later in the season. However, the life history of the weevils likely also influenced the relative impact of weevils added early in the season compared with those added later. Those added early had time to build in population numbers while going through several generations, although they were subject to the artificial limitation of having only a single plant on which to reproduce. In addition, *R. latipes* adults stop laying eggs in mid-September in preparation for overwintering (Lake 2007), while *P. perfoliata* continues to produce seeds up until the time of the first heavy frost, which occurred in early November in Delaware in 2006 and

2007. Thus weevils added later in the season would have had less time to reproduce and increase in numbers.

It is difficult to say whether the numbers of weevils added to the field cages were realistic compared to the field situation, because of the growth form of the plant in nature. Because mile-a-minute weed is an annual plant and naturally growing plants were used, the plants in the cages were no different in age or establishment than the naturally occurring stand, except that they were relieved from crowding by conspecifics in the cages, and in fact from all other competitors in the 2006 trial. In a severe mile-a-minute infestation in North America, initial seedling densities can be as high as 500 or more per m² (unpublished data), resulting in masses of intertwined plants by early June. This makes it impossible to isolate weevil numbers on a single plant. However, we have monitored weevil populations on mile-a-minute foliage in 1 m by 1 m quadrats, which to some degree may be related to densities within the approximately 1 m² cages. Two years following weevil releases at three sites in southeastern Pennsylvania, weevil densities in May, shortly after the emergence of overwintered adults, averaged from 8 to 16 weevils per m² of mile-a-minute foliage at the sites (unpublished data). This suggests that the 5 and 10 weevils per plant release rates used in the field cages were not unrealistic even a short time following weevil establishment. Peak numbers at these sites occurred in August, and averaged as high as 133 weevils per m² of mile-a-minute foliage. The higher levels of 20 and 40 weevils per plant in May could be achievable in areas where weevil populations have established for longer periods of time, or through laboratory rearing and release.

An additional confounding factor with these experiments relates to artificial confinement of the weevils on the plants. On the one hand, by preventing dispersal and possible predation, the cages may have confined weevils at higher densities than would occur naturally. On the other hand, the low numbers of weevils counted in the cages in the second destructive sample in 2007 suggests that high densities of weevils on single plants limited their ability to reproduce and led to weevil mortality later in the season in the cages. The dispersal behavior of *R. latipes* in the field is not known, but will be the subject of future studies.

Plant mortality was perhaps the most important outcome of insect feeding under conditions with plant competition in these experiments. Myers and Risley (2000) noted that successful biological control of plants that produce many seeds may in fact require plant mortality rather than just reduction in seed production, where plant populations are not seed-limited. Although time will tell whether *R. latipes* populations will build to the point where plant mortality occurs regularly in the field, this has already been observed in some areas (Furchak, 2007; Lake, 2007).

Louda et al. (1990) review numerous cases where differential herbivory has been shown to alter the outcome of plant competition. Although we did not directly test the interaction of herbivory and plant competition, the results of our tests collectively suggest that observed effects of

R. latipes feeding on *P. perfoliata* will impact plant growth and reproduction, and can put affected plants at a substantial competitive disadvantage.

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