A Review of World-Wide Biological Control Efforts for the Family Adelgidae

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Abstract

A summary of biological control efforts on various *Pineus* and *Adelges* species based on published literature is discussed. The aim of this review is to learn from these individual programs to aid our continuing efforts in biological control of the hemlock woolly adelgid, *Adelges tsugae* Annand, in the eastern United States. By studying past programs, general patterns may show up that will improve the success and predictability of biological control.

Keywords:

Biological control, Adelgidae, exotic pest, *Tsuga*, hemlock.

Introduction

The hemlock woolly adelgid (HWA), *Adelges tsugae* Annand, is a serious threat to hemlock landscape and forest stands in the eastern United States (McClure 1996). Eastern hemlock (*Tsuga canadensis* (L.) Carrière) and Carolina hemlock (*T. caroliniana* Engelmann) are very susceptible to HWA attack and infested trees have died in as little as four years (McClure 1991). Hemlock woolly adelgid is exotic to eastern North America (McClure 1987). First reported in the eastern United States in Virginia in 1952 in an ornamental setting (Souto et al. 1996), it has spread to forests where it occurs along the eastern seaboard from North Carolina to southern New England (Salom et al. 2001). The main front of the HWA infestation is advancing at approximately 25 km per year (McClure 2001).

In 1993, the Hemlock Woolly Adelgid Working Group was established in the eastern United States to coordinate research efforts to reduce the impact of the hemlock woolly adelgid and slow its spread in eastern hemlock forest ecosystems (Reardon and Bullard, 1996). Biological control was identified as an area of emphasis for management of HWA in a forest setting under the USDA Forest Service Technology Enterprise Team (Onken 1996; Reardon and Bullard 1996). Studies by McClure (1987) and Montgomery and Lyon (1996) in Connecticut, and Wallace and Hain (2000) in North Carolina and Virginia, documented a number of native or established predators associated with HWA, but they were generally found at densities too low to significantly impact populations of HWA. No parasitoids that attack any member of the family Adelgidae are known. A classical biological program for HWA in eastern United States was therefore initiated. Several predators are

currently being investigated and discussed later in the paper.

Biological control of forested insects is well documented (Pschorn-Walcher 1977; Dahlsten and Mills 1999, and references therein). Classical biological control (i.e., importation of natural enemies against introduced pests) is the most common approach to biological control in forestry (Dahlsten and Mills 1999). Dahlsten and Mills (1999) presented data from the International Institute of Biological Control (IIBC) database of worldwide biological control introductions. The number of importations of parasitoids and predators against forest insect pests, the percentage of successful establishments, and those that have achieved some degree of control were summarized. Homopteran pests comprised about 24% of all forestry pests targeted for biological control. The orders Lepidoptera, Hymenoptera, and Coleoptera comprised 36%, 21%, and 17%, respectively. Overall, 78% of importations of natural enemies that targeted forestry pests involved parasitoids. However, more than 80% of exotic predators used targeted homopteran pests (Dahlsten and Mills 1999).

The objective of this paper is to summarize predator introductions for biological control of adelgids to date and provide examples of successful establishments of these target pests. This information may be useful for future attempts at new introductions of HWA predators.

Summary of Biological Control Programs of Adelgids

Several biological control programs have been carried out on adelgid pests. Previous attempts to control adelgids using natural enemies were more successful for the genus *Pineus* (Culliney et al. 1988; Zondag and Nuttall 1989; Mills 1990) than for *Adelges* (Mitchell and Wright 1967; Amman and Speers 1971; Clark et al. 1971; Clausen 1978; Harris and Dawson 1979; Schooley et al. 1984). Table 1 summarizes predators that have been released to control various adelgid pests.

Pineus laevis[1] . Biological control of *Pineus laevis* Maskell in Australia failed because of the lack of establishment of the five predators released (Clausen 1978). However, successful control of *P. laevis* was achieved in both Chile and New Zealand with the European chamaemyiids *Leucopis (Neoleucopis) obscura* Haliday (Mills 1990) and *L. (N.) tapiae* Blanchard (Zondag and Nuttall 1989), respectively.

Pineus pini. In Hawaii, *Pineus pini* (Macquart) was successfully controlled with the introduction and establishment of *L. (N.) tapiae* (Culliney et al. 1988; Greathead 1995) and *Leucopis nigraluna* McAlpine from Pakistan (Mills 1990). In Kenya, *Tetraphleps raoi* Ghauri (Hemiptera: Anthocoridae) was successfully introduced into Kenya from Pakistan for biological control of *P. pini* and established in pine plantations (Mailu et al. 1980; Aloo and Karanja 1986). The establishment of *T. raoi* was followed by a decline in field populations of *P. pini* (Aloo and Karanja 1986), but successful biological control of *P. pini* has not yet been reported.

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[1] According to Blackman and Eastop (1994), this species is *Pineus boerneri* Annand, described from *Pinus radiata* in California, but erroneously recorded under the name *Pineus laevis*.

Adelges piceae. The classical biological control program for the balsam woolly adelgid, *Adelges piceae* (Ratzeburg) in North America is well documented (Smith and Coppel 1957; Mitchell and Wright 1967; Amman and Speers 1971; Clark et al. 1971; Harris and Dawson 1979; Schooley et al. 1984). More than 25 species of predators released over approximately 35 years resulted in eight European species becoming established, including *Laricobius erichsonii* Rosenhauer. Despite establishment, these introduced predators failed to provide significant control of *A. piceae* (Clark et al. 1971; Clausen 1978; Schooley et al. 1984). Reasons suggested for lack of success were attributed to poor synchronization between various predators and *A. piceae*, inadequate searching ability of predators, inability to adapt to harsh winter climates in eastern Canada, poor overwintering conditions in the soil, and inability of host trees to withstand even low populations *of A. piceae* (Mitchell and Wright 1967; Clark et al. 1971; Clausen 1978; Harris and Dawson 1979; Schooley et al. 1984). This indicates that random introduction of multiple species of natural enemies does not guarantee success. We need to consider better climate matching between regions of collection and target areas of release, and the behavior of natural enemies. Some natural enemies are better suited to high or low pest densities, and others may be specialized for specific niches, e.g., trunk versus crown infestations. Better reconstruction of the guilds of natural enemies that occur in the native range of the pest may have resulted in a better outcome for biological control of *A. piceae*.

Adelges tsugae. Research on biological control of the hemlock woolly adelgid began in the early 1990s. Field surveys of native and established natural enemies of HWA in eastern United States were conducted by McClure (1987) and Montgomery and Lyon (1996) in Connecticut and Wallace and Hain (2000) in North Carolina and Virginia. In both regions, natural enemies were found at densities too low to significantly reduce populations of HWA. In addition, most natural enemies were generalist predators (Montgomery and Lyon 1996; Wallace and Hain 2000). Foreign exploration in Japan (Cheah and McClure 1996) and China (Montgomery et al. 2000; Yu et al. 2000) for candidate natural enemies of HWA was initiated in 1992 and 1996, respectively. Two species, *Diapterobates humeralis* (Hermann) (Oribatida: Ceratozetidae) and *Pseudoscymnus tsugae* Sasaji and McClure collected in Japan, were selected as the most promising candidates for introduction into North America (Cheah and McClure 1996). Observations on foraging behavior of *D. humeralis* revealed that these mites did not feed on adelgid eggs and nymphs, but consumed the woolly filaments that surrounded HWA eggs. This feeding behavior dislodged eggs (McClure 1995a). Although *D. humeralis* resulted in approximately 65% mortality of HWA eggs in Japan (McClure 1995a), its low fecundity, difficulty of lab culture, and its distribution throughout temperate regions of the Northern Hemisphere, made it an unsuitable candidate for release in North America (Cheah and McClure 1996).

In Japan, *P. tsugae* was found in more than 30% of forest and ornamental sites sampled, where adelgid mortality was observed to be greater than 85% (McClure 1995b). *Pseudoscymnus tsugae* was imported into eastern United States and is undergoing laboratory and field evaluations as a potential biological control agent of HWA (Cheah and McClure 1996, 1998). Quarantine studies in Connecticut revealed that *P. tsugae* possesses many attributes of a successful biological control agent (Cheah and McClure 1996, 1998). In addition, it is amenable to mass culture in the laboratory (Cheah and McClure 1998; McClure and Cheah 1999). Since 1995, more than 160,000 adults of *P. tsugae* have been mass-reared and released in forests of Connecticut, New Jersey, and Virginia (McClure 2001; Salom et al. 2001). Results have been encouraging where *P.*

tsugae has been released (McClure and Cheah 1999; Cheah and McClure 2000; McClure 2001). Compared with control sites, HWA densities were reduced 47 to 87% (McClure 2001).

In China, the following families with number of species in parenthesis were collected from HWA infested hemlocks: Coccinellidae (54), Anthocoridae (4), Miridae (3), Syrphidae (2), and Cecidomyiidae (1) (Yao and Hongbin 1998; Montgomery et al. 2000; Yu et al. 2000). Three species, *Scymnus (Neopullus) sinuanodulus* Yu & Yao, *S. (N.) camptodromus* Yu & Liu, and *S. (N.) ningshanensis* Yu & Yao, in the family Coccinellidae (subfamily: Scymninae), were imported into the eastern United States for further study under quarantine (Yao and Wang 1998). Lu and Montgomery (2000) determined that all three species are univoltine and feed on HWA, preferring eggs to other stages. However, *S. (N.) camptodromus* eggs undergo a diapause (Lu and Montgomery 2000), making it difficult to culture and therefore unsuitable as a potential candidate for release (M.E. Montgomery personal communication 2001). Field evaluation of *S. (N.) sinuanodulus* and *S. (N.) ningshanensis* using sleeve cages began in 1999 and 2001, respectively (M.E. Montgomery personal communication 2001; Salom et al. 2001). Although these lady beetles reduced the population of HWA significantly, this reduction may not be sufficient to prevent HWA from causing damage (M.E. Montgomery personal communication 2001).

Laricobius nigrinus Fender (Coleoptera: Derodontidae), native to western North America, has been observed in close association with HWA in British Columbia, Canada (L. Humble personal communication 1996), where HWA is not considered a pest. In 1998, field studies and quarantine evaluation were initiated in British Columbia and Virginia, respectively (Zilahi-Balogh 2001). *Laricobius nigrinus* adults feed on developing sistens nymphs in the fall and winter at temperatures above 0°C. Larvae feed on the eggs of the progrediens generation and migrate to the soil by the end of the progrediens egg stage (Zilahi-Balogh 2001). Host specificity tests revealed that *L. nigrinus* has a narrow host range, preferring to oviposit and feed on adelgid than on non-adelgid homopterans. In addition, larvae only completed development on a diet of HWA (Zilahi-Balogh et al. in press). In September 2000, *L. nigrinus* was removed from quarantined status. Caged field trials to evaluate feeding voracity and survivorship were initiated in February 2001. Results for the first year are summarized by Lamb et al. (2002).

Summary

Successful biological control of *Pineus laevis* and *P. pini* have been demonstrated with the introduction and establishment of various chamaemyiid species (genus *Leucopis*) in Chile and New Zealand (*P. laevis*), and in Hawaii (*P. pini*) (Culliney et al. 1988; Zondag and Nuttall 1989; Mills 1990; Greathead 1995). An anthocorid predator, *Tetraphleps raoi*, introduced into Kenya for biological control of *P. pini*, has also been successful in reducing populations of *P. pini* (Mailu et al. 1980; Aloo and Karanja 1986). However, successful biological control of *Adelges piceae* was not achieved even with the large number of species introduced (Clark et al. 1971; Clausen 1978; Schooley et al. 1984). To date, *Pseudoscymnus tsugae* is the only predator which is being mass-reared and released in the field for control of HWA in the eastern United States. The two *Scymnus* species and *L. nigrinus* show potential and attempts should be made to mass rear them for release. Since *P. tsugae* (McClure and Cheah 1999) and *S. sinuanodulus* (Lu and Montgomery 2001)

Table 1. Summary of Predator Releases Against the Family Adelgidae.

Target Pest	Target Region	Year of Release	Origin of Species Released	Species Released	Agent Established	References[g]
Adelges piceae	Canada/USA[a]	1933-1969		Coleoptera: Coccinellidae		
(Ratzeburg)			Europe	*Aphidecta obliterata* (L.) [b]	Yes[b]	5, 7, 9
				Exochomus quadripustulatus (L.)[d]	No[e]	1, 5
				Scymnus (Pullus) impexus Mulsant [b]	Yes[b]	1, 2, 5, 6
			India/Pakistan	*Coccinella (Adalia) luteopicta* Mulsant[b]	No	2, 4, 5, 7
				Adalia tetraspilota (Hope) [b]	No	2, 5, 7
				Coccinella septempunctata L. [e]	No[e]	7
				Exochomus lituratus Gorhamb	No	2, 5, 7
				Exochomus uropygialis Mulsant[b]	No	2, 5, 7
				Harmonia breiti Mader[b]	No	2, 3, 5, 7
				Harmonia (Leis) dimidiata (Fabricius) [c]	No[e]	2, 5
				Harmonia (Ballia) eucharis [=*dianae*] Mulsant[b]	No	2, 5, 7
				Oenopia (Synharmonia) conglobata (L.) [c]	No	2, 5
				Oenopia sauzeti Mulsant[c]	No	2
			Japan	*Adalia ronina* (Lewis) [= *A. conglomerata* L.] [d]	No	5, 8
				Chilocorus kuwanae Silvestric	No[e]	2, 5
			Australia	*Diomus (= Scymnus) pumilio* (Weise) [b]	No	2, 5, 7
				Coleoptera: Derodontidae		
			Europe	*Laricobius erichsonii* Rosenhauerb	Yes[b]	1, 2, 4, 5, 6, 8

Table 1. continued

Target Pest	Target Region	Year of Release	Origin of Species Released	Species Released	Agent Established	References[g]
Adelges piceae (Ratzeburg)	Canada/USA			Diptera: Cecidomyiidae		
			Europe	*Aphidoletes thompsoni Möhnb*	Yes[b]	1, 2, 4, 5, 6, 7
				Diptera: Chamaemyiidae		
			Europe	*Cremifania nigrocellulata Czerneyb*	Yes[b]	1, 4, 5, 6, 7, 9
				Leucopis (Neoleucopis) atratula Ratz. [d]	Yes[c]	7, 9
				Leucopis hennigrata McAlpine (= L. sp.nr. melanopus Tanasijtshuk) [b]	Yes[d]	7
				Leucopis (Neoleucopis) obscura Halidayb	Yes[b]	1, 2, 7
				Lipoleucopis praecox de Meijd	No	5
				Diptera: Syrphidae		
			Europe	*Cnemodon* spp. [d]	No	1
				Hemiptera: Anthocoridae		
			India/Pakistan	*Tetraphleps abdulghani Ghaurid*	No	7
				Tetraphleps raoi Ghaurid	No	7
				Neuroptera: Hemerobiidae		
			Europe	*Hemerobius nitidulus Fabriciusd*	No	1, 5
				Hemerobius stigma Stephensd	No	1, 5
				Neuroptera: Chrysopidae		
			India/Pakistan	*Chrysopa* spp. [c]	No	2, 5
				Acari: Erythraeidae		
			India/Pakistan	*Balaustium* spp. [d]	No	7
Adelges tsugae Annand	Eastern USA	1995 to present		Coleoptera: Coccinellidae		
			Japan	*Pseudoscymnus tsugae* Sasaji & McClure	Yes	10, 11

Table 1. continued

Target Pest	Target Region	Year of Release	Origin of Species Released	Species Released	Agent Established	References[g]
Pineus laevis[h] (Maskell)				Coleoptera: Coccinellidae		
			Europe	*Exochomus quadripustulatus* (L.)	No	5
	Australia	1932-1940		Neuroptera: Hemerobiidae		
			UK	*Westmaelius concinnus* Stephens	No	5
				Diptera: Chamaemyiidae		
			UK	*Leucopis (Neoleucopis) obscura* Haliday	No	5
				Lipoleucopis praecox de Meij	No	5
			California	*Leucopis atrifacies* Ald.	No	5
	Chile	1945	Europe	*Leucopis (Neoleucopis) obscura* Haliday	Yes	12
	New Zealand	1926-1934		Coleoptera: Coccinellidae		
			Australia	*Diomus (=Scymnus) pumilio* (Weise)	No	13
				Diptera: Chamaemyiidae		
			UK	*Leucopis(Neoleucopis) tapiae* Blanchard	Yes	13
				Neuroptera: Hemerobiidae		
			UK	*Hemerobius stigma* Stephens	No	13
Pineus pini (Macquart)				Diptera: Chamaemyiidae		
	Hawaii	1972, 1977	Pakistan	*Leucopis nigraluna* McAlpine	Yes	14
		1976-1979	Europe	*Leucopis (Neoleucopis) tapiae* Blanchard[f]	Yes	14, 15
	Kenya			Hemiptera: Anthocoridae		
		1975	Pakistan	*Tetraphleps raoi* Ghauri	Yes	12, 16, 17
				Diptera: Chamaemyiidae		
		1970-1975		*Leucopis nigraluna* McAlpine	No	15
		1970-1975	Europe	*Leucopis(Neoleucopis) tapiae* Blanchard	No	15
				Leucopis argenticollis Zetterstedt	No	15

[a] Canada 1933-1969, USA 1955-1965;[b]east and west; [c]west only; [d]east only; [e]did not establish on *A. piceae*, but established elsewhere (8);
[f] previous reported as *L. obscura*, but subsequently determined to be *L. tapiae* (15).
[g] 1. Smith and Coppel 1957; 2. Mitchell and Wright 1967; 3. Amman and Speers 1971; 4. Clark et al. 1971; 5. Clausen 1978; 6. Harris and Dawson 1979; 7. Schooley et al. 1984; 8. Gordon 1985; 9. Humble 1994; 10. McClure and Cheah 1999; 11. Cheah and McClure 2000; 12. Mills 1990;
13. Zondag and Nuttall 1989; 14. Culliney et al. 1988; 15. Greathead 1995; 16. Mailu et al. 1980; 17. Aloo and Karanja 1986.
[h] According to Blackman and Eastop (1994), species is *P. boerneri* Annand, described from *Pinus radiata* in California, but erroneously recorded under the name *Pineus laevis*.

larvae are active later than *L. nigrinus* (i.e., present during the last third of progrediens egg stage and the complete sistens egg stage), we expect little temporal overlap of these species with *L. nigrinus* larvae and therefore little competition.

After a decade, we have shown that biological control can reduce populations of HWA. However, complete success may not be realized for another two decades unless a complex of predators that complement each other can be established. To date, only coleopteran predators have been investigated. Two families of predators that have shown a measurable reduction in the population of their target hosts (i.e., *Pineus*) are Chaemymiidae (Diptera) and Anthocoridae (Hemiptera). Future foreign exploration in Asia and evaluation of natural enemies of HWA should include these and other orders.

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