

Egg Parasitoids of *Sophonia rufofascia* (Homoptera: Cicadellidae) in Hawaii Volcanoes National Park

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Parasitism of the leafhopper *Sophonia rufofascia* (Kuoh and Kuoh), a recent immigrant that has become a widespread pest in Hawaii, was examined in a 1-year survey in Hawaii Volcanoes National Park. Samples of young leaves of four plant species infested with eggs of *S. rufofascia* were collected at five sites ranging from 880 to 1190 m in elevation. Leafhopper eggs were parasitized principally by three species of Mymaridae (Hymenoptera): *Polynema* sp., *Schizophragma* sp. probably *bicolor* (Dozier), and *Chaetomyrma* sp. Although parasitism by each species fluctuated at levels usually below 10%, all three were detected consistently across most host plants, sites, and sample periods. Total parasitism differed at a marginally significant level among host plants and sites, but not among sample periods. Total parasitism averaged 14.3% (maximum: 26.3%) on *Dodonaea viscosa* Jacquin, 10.6% (maximum: 17.5%) on *Myrica faya* Aiton, 8.7% (maximum: 29.5%) on *Metrosideros polymorpha* Gaudich-Beaupre, and 1.6% (maximum: 4.3%) on *Vaccinium reticulatum* Smith. Parasitism was generally higher at sites lower in elevation. Further monitoring is recommended to determine whether parasitism will increase to levels that can effectively suppress *S. rufofascia* populations. The efficacy of natural enemies already present in Hawaii is important because concern over nontarget impacts on endemic leafhoppers makes introduction of new biological control agents difficult. © 2001 Academic Press

Key Words: *Sophonia rufofascia*; leafhopper egg parasitoids; Mymaridae; *Polynema* sp.; *Schizophragma* sp.; *Chaetomyrma* sp.; *Myrica faya*; biological control.

INTRODUCTION

Sophonia rufofascia (Kuoh and Kuoh) was first detected in Hawaii in 1987 on the island of Oahu (Heu and Kumashiro, 1989) and within 5 years had spread to all major neighboring islands (Culliney, 1998). By 1993, outbreaks of *S. rufofascia* were observed in areas of native forest (Palmer, 1993) and on commercially grown guava (*Psidium guajava* L.) (Jones *et al.*, 1998), elevating it to the status of a major pest. In contrast, the leafhopper is not well known in its native range; it has been collected in China and elsewhere in Asia on a variety of plants, including tea, rice, mulberry, oak, apricot, and fig (Esaki and Ito, 1954; Ahmed and Mahmood, 1969; Huang, 1994). In Hawaii, Fukada (1996) recorded *S. rufofascia* developing on over 300 plant species in 87 families, including 16 rare endemic species. By 1995, the leafhopper was widespread on the six largest Hawaiian islands and distributed from sea level to 1460 m in elevation (Fukada, 1996).

S. rufofascia feeds and oviposits preferentially in young foliage (Fukada, 1996; Culliney, 1998; Jones *et al.*, 2000). Leafhopper feeding typically produces localized chlorosis in leaf tissue, and in extreme cases, affected leaves may become necrotic. No evidence of involvement of phytoplasmas, pathogens commonly transmitted by other leafhoppers, was found in guava orchards infested by *S. rufofascia* (Jones *et al.*, 1998). Through oviposition into leaf mid-veins, the leafhopper can damage vascular bundles of some hosts to the point of causing death of the distal tissue (Culliney, 1998; Jones *et al.*, 2000).

S. rufofascia has been implicated in the death of large patches of native uluhe fern, *Dicranopteris linearis* (Burman), the dominant understory species in Hawaii's native wet forests (Palmer, 1993; Culliney, 1998). Jones *et al.* (2000) demonstrated that *S. rufofascia* feeding causes premature senescence in uluhe fronds, but conclusive evidence that the leafhopper

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TABLE 1

Sites and Host Plants Sampled in Hawaii Volcanoes National Park, September 1997–August 1998

Site	Elevation (m)	Host plants sampled			
		<i>Dodonaea viscosa</i>	<i>Metrosideros polymorpha</i>	<i>Myrica faya</i>	<i>Vaccinium reticulatum</i>
Kipuka Kahalii	880	X	X	X	
Puhimau Crater	1100	X	X	X	
Devastation Trail	1130	X	X	X	
Crater Rim	1160		X		X
Kipuka Puaulu	1190	X	X		

caused widespread uluhe dieoff is lacking. Uluhe dieoff leads to problems with erosion on the steep slopes of forest watersheds (Scott, 1969) and permits invasion by alien weeds (P. Follett, unpublished data). Fortunately, in the past few years the rate of uluhe dieoff appears to have slowed, and in some cases dead patches are being recolonized by surrounding live uluhe (P. Follett, unpublished data).

High populations of *S. rufofascia* have been detected in Hawaii Volcanoes National Park on the island of Hawaii since 1994 in association with the weed *Myrica faya* Aiton (P. Yang and D. Foote, unpublished data). In some areas of the park invaded by *M. faya*, there has been extensive dieback of ohia-lehua, *Metrosideros polymorpha* Gaudich-Beaupre, a dominant tree of native Hawaiian forests. Although cases of widespread ohia-lehua dieoff precede the arrival of *S. rufofascia* (Mueller-Dombois, 1993), the role of leafhoppers in areas of recent ohia-lehua decline is being investigated (L. Lenz, personal communication).

The ability of *S. rufofascia* to invade Hawaiian forest habitats, where conventional insecticidal control is unfeasible, makes this pest a prime candidate for classical biological control. However, control of leafhoppers by natural enemies already present in Hawaii may render a costly program of foreign exploration and host screening unnecessary. In the course of previous studies, several parasitoid species were discovered attacking eggs of *S. rufofascia* (Yang *et al.*, 2000). To determine species composition and abundance of egg parasitoids currently utilizing *S. rufofascia*, we conducted a 1-year survey in Hawaii Volcanoes National Park (HAVO) on the island of Hawaii.

MATERIALS AND METHODS

Sampling

Leaves of four plant species commonly attacked by *S. rufofascia* were collected at five sites ranging from 880 to 1190 m in elevation in HAVO. Because all plant species could not be found in sufficient abundance at any single site, two to three species were sampled at each site (Table 1). Three of the host plants are com-

mon Hawaiian natives: ohia-lehua, *M. polymorpha*; a'ali'i, *Dodonaea viscosa* Jacquin; and ohelo, *Vaccinium reticulatum* Smith. The fourth host plant, fire-tree, *Myrica faya*, is an invasive weed that has been spreading in HAVO since 1961 (Vitousek *et al.*, 1987).

Young, fully expanded leaves were collected from five separate plants of each species at each site. Collections were repeated at intervals of 6 weeks, approximately twice per leafhopper generation (Duan and Messing, 2000), from September, 1997 to August 1998. *S. rufofascia*-infested leaves of guava, *Psidium guajava* L., were collected in Hilo, Hawaii, 40 km north of the park, on two occasions during the survey period.

Samples were returned to the Kilauea Field Station laboratory at HAVO, where each leaf was examined using backlighting. Leaves without visible *S. rufofascia* oviposition scars were discarded, leaving a sample of 20–60 leafhopper-infested leaves from each plant. Each sample was held separately in a plastic Ziploc bag (8 × 16 cm; DowBrands, Indianapolis, IN). Samples were checked every 2–3 days; emerged *S. rufofascia* and parasitoids were removed and placed in 70% ethanol.

After 3 weeks, leaves were dissected under magnification. Leaves of *D. viscosa* were usually dissected after 2 weeks due to problems with mold. Some scars initially identified as oviposition sites were found to lack eggs. Such scars, apparently formed in response to leafhoppers probing without laying eggs, were deleted from our sample total. The remaining oviposition scars were classed into two main categories: (1) scars from which *S. rufofascia* emerged, and (2) scars from which parasitoids emerged. Emergence of *S. rufofascia* was distinguished by a narrow, elongate opening with remains of the egg chorion protruding at one end (Culliney, 1998). Parasitoid emergence holes were round and lacked remains of chorion. Occasionally, partially developed leafhoppers or parasitoids were dissected. These were totaled with unparasitized and parasitized eggs, respectively.

Parasitoids were grouped initially into morphospecies. Midway through our survey, and again at the end, representatives of all morphospecies were mounted

TABLE 2

Parasitoids Emerged from Leaves Bearing *S. rufofascia* Oviposition Scars, Collected on Hawaii September 1997–August 1998

Sample totals	Family	Species	Host plant				
			<i>Dodonaea viscosa</i>	<i>Metrosideros polymorpha</i>	<i>Myrica faya</i>	<i>Vaccinium reticulatum</i>	<i>Psidium guajava</i>
No. plants			141	142	118	58	11
No. leaves			3659	3578	3355	1191	65
No. <i>S. rufofascia</i> oviposition scars			3720	4282	3432	1522	85
No. parasitoids emerged	Mymaridae	<i>Polynema</i> spp.	282	72	32	30	—
		<i>Schizophragma</i> sp. prob. <i>bicolor</i>	63	90	115	5	—
		<i>Chaetomyrmar</i> sp.	53	135	93	—	42
		<i>Alaptus</i> sp.	22	1	—	—	—
		<i>Stethynium</i> spp.	1	—	7	—	—
		<i>Anagrus</i> sp.	—	—	2	1	—
	Trichogrammatidae	<i>Oligosita</i> sp.?	3	—	1	—	—
	Encyrtidae	?	—	—	1	—	—
	Eulophidae	?	—	—	1	—	—
	Unknown ^a	Unknown ^a	132	85	105	—	—

^a Parasitoids emerged in the field before samples were collected.

and identified. Voucher specimens have been deposited in the insect museum of the Department of Entomology, University of Hawaii, Honolulu.

Analysis

Parasitism was calculated from numbers of emerged and dissected parasitoids as a percentage of oviposition scars for each plant sampled. Samples with fewer than 15 oviposition scars (< 3% of all samples) were excluded as too small. Variables calculated included total parasitism, parasitism by individual species of parasitoids, and parasitism by unknown species. Total parasitism was based on counts of parasitoid emergence holes plus dissected parasitoids. Parasitism by each species was based on emerged parasitoids plus dissected parasitoids, which typically could be identified to morphospecies. Unknown parasitism (i.e., by parasitoids that emerged before sampling) was calculated from the difference between number of parasitoid emergence holes and totals of all morphospecies. Because samples were collected on different dates at different sites, data were grouped for analysis into nine sampling periods with durations of approximately 6 weeks each.

Effects of host plant, site, and sampling period on total percentage parasitism were examined using repeated-measures ANOVA (Littell *et al.*, 1996). Some data were excluded from analysis to resolve problems with unbalance: data from the host *V. reticulatum*, because it was sampled at only one site; and data from *M. polymorpha* at the Crater Rim site, where adequate

samples of this host were obtained on only three dates. Data were first averaged across plants sampled at each site/host plant/period to reduce problems with zero values. Sample means were transformed by the square-root method before ANOVA to improve normality and homogeneity of variance. Effects found to be significant in ANOVA were examined further using Tukey HSD (SAS Institute, 1994).

Effects of host plant and site on percentage parasitism by each parasitoid species were examined using the Kruskal-Wallis test (SAS Institute, 1994). A non-parametric analysis was chosen because the data (means across plant samples) were strongly skewed toward zeros and very small values.

RESULTS

Parasitoid Species

In total, 1055 parasitoids were recovered from our samples and grouped into morphospecies. Of these specimens, 169 were formally identified. Only 3 specimens were found misclassified as morphospecies, an error rate of less than 2%. A total of 3888 leafhopper nymphs were recovered, and all except 4 were identified as *S. rufofascia*. (Four leafhopper nymphs, probably of a single native species, emerged from *M. polymorpha* leaves collected 29 May, 1998, at Kipuka Kahalii.)

Over 95% of the parasitoids collected in this survey belong to three genera of mymarids: *Polynema* (39%), *Schizophragma* (26%), and *Chaetomyrmar* (30%) (Table

2). The majority of *Polynema* (49 out of 63 specimens formally identified) appear to belong to a single species. The remaining specimens represent 2–4 other species of *Polynema*. This genus is in need of revision, and consequently its members are not currently identifiable to species (Beardsley and Huber, 2000). The *Schizophragma* sp. is probably *Schizophragma bicolor* (Dozier), and the *Chaetomyrmar* sp. appears to be an undescribed species new to Hawaii.

The *Alaptus* sp., recovered in low numbers primarily from *D. viscosa*, is probably a result of contamination of our samples with psocopterans, which are the usual hosts of *Alaptus* (Huber, 1986) and which are common on *D. viscosa* (M. T. Johnson, unpublished data). *Stethynium* spp. (probably two species in our samples) and *Anagrus* sp. are known to parasitize leafhopper eggs (Huber, 1986), but their association with *S. rufofascia* appears to be weak, given the small numbers recovered (Table 2). Similarly, the association between *S. rufofascia* and the few nonmyrmarids recovered may be only incidental.

A substantial number of parasitoids emerged from oviposition scars before our samples were collected, and therefore their identities remain unknown (Table 2).

Variation in Total Parasitism

Total parasitism was low at all HAVO sites throughout our sampling effort, never exceeding 30% (Fig. 1). Differences in total parasitism were marginally significant among host plant species ($F = 3.83$; $df = 2, 5$; $P = 0.098$) and among sites ($F = 4.08$; $df = 3, 5$; $P = 0.082$), but not among sample periods (linear component: $F = 0.06$; $df = 1, 64$; $P = 0.81$; quadratic component: $F = 0.23$; $df = 1, 64$; $P = 0.63$). Total parasitism was highest on *D. viscosa*, followed by *M. faya* and *M. polymorpha* (Table 3). Parasitism of *S. rufofascia* on *V. reticulatum* was very low at the one site where this host plant was sampled (Table 3, Fig. 1). In general, total parasitism decreased with increasing elevation of sample site (Table 3), with the exception of the 1190 m site, where parasitism on *D. viscosa* in particular was relatively high (Fig. 1).

Fluctuation in total parasitism across sample periods tended to decrease from *M. polymorpha* (mean coefficient of variation \pm SE: $53.3\% \pm 6.0$) and *D. viscosa* ($41.6\% \pm 6.8$) to *M. faya* ($28.0\% \pm 7.8$) (Fig. 1), but overall differences among these host plants were only marginally significant ($F = 3.32$; $df = 2, 9$; $P = 0.083$).

Variation among Parasitoid Species

Host plant species significantly affected percentage parasitism by *Polynema* spp., *Schizophragma* sp., and unknown parasitoids (Table 4). Parasitism by

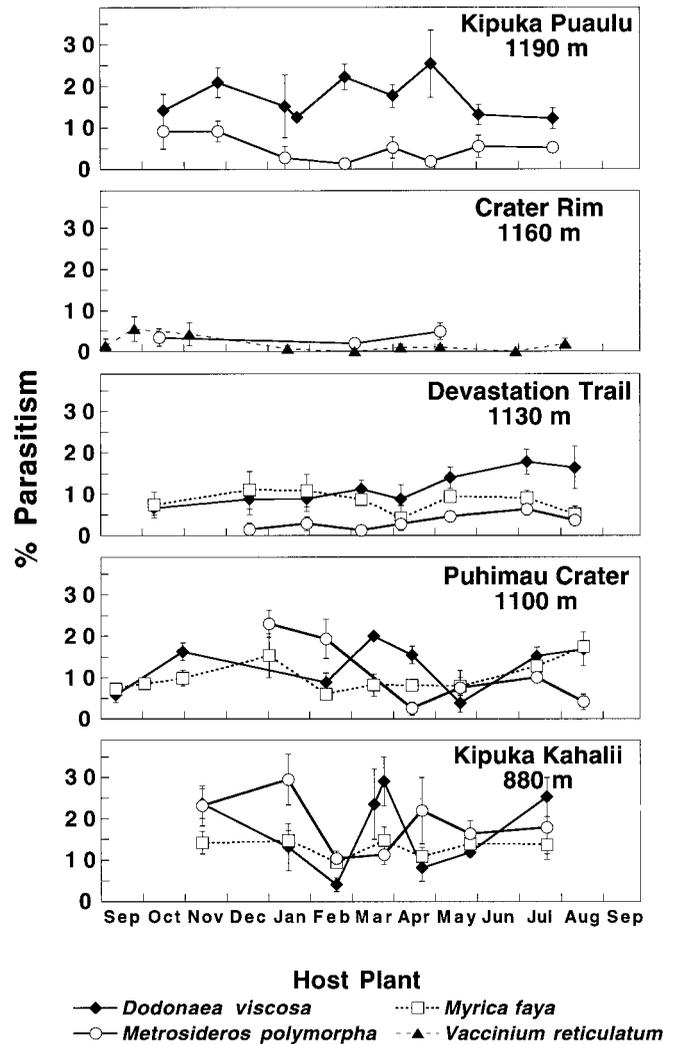


FIG. 1. Total percentage parasitism (mean \pm SE) of *S. rufofascia* eggs on four host plant species from September 1997 to August 1998 at five sites in Hawaii Volcanoes National Park.

Polynema spp. was highest on *D. viscosa*. Parasitism by *Schizophragma* sp. was highest on *M. faya*. Parasitism by *Chaetomyrmar* sp. did not differ significantly among host plants in HAVO. This *Chaetomyrmar* sp. was the only parasitoid species collected from guava near sea level in Hilo (Table 2).

Parasitism differed significantly among sites for *Schizophragma* sp., *Chaetomyrmar* sp., and unknown parasitoids, and in every case was higher at low elevation sites (Table 4). Parasitism by *Polynema* spp. did not differ significantly among sites.

DISCUSSION

In this survey, *S. rufofascia* eggs in HAVO were attacked principally by three species of parasitoids: *Polynema* sp., *Schizophragma* sp., and *Chaetomyrmar*

TABLE 3

Effects of Host Plant and Site on Total Parasitism of *S. rufofascia* Eggs

Effect	Level	% parasitism		Frequency of zero parasitism	
		Mean ^a ± SE	Range	% of plant samples	<i>n</i>
Host plant	<i>Dodonaea viscosa</i>	14.3 ± 3.4 a	3.9–26.3	3.7	135
	<i>Myrica faya</i>	10.6 ± 3.5 ab	4.3–17.5	4.4	113
	<i>Metrosideros polymorpha</i>	8.7 ± 3.5 b	1.3–29.5	22.1	136
	<i>Vaccinium reticulatum</i>	1.6 ± 4.4 c	0–4.3	68.2	44
Site	Kipuka Kahalii (880 m)	15.9 ± 3.6 a	4.0–29.5	2.0	100
	Puhimau Crater (1100 m)	11.3 ± 3.3 ab	2.5–23.0	6.3	96
	Kipuka Puauulu (1190 m)	11.2 ± 3.7 ab	1.3–25.4	13.2	76
	Devastation Trail (1130 m)	7.9 ± 3.6 b	1.3–17.8	18.2	99
	Crater Rim (1160 m)	2.1 ± 4.1 c	0–4.9	61.4	57

^a Means (based on plant sample means averaged across sample periods) in the same column followed by the same letter are not significantly different (Tukey HSD test; $P < 0.05$). Effects of host plant and site were tested separately.

sp. Although parasitism by each species fluctuated at levels usually below 10%, all three were detected consistently across host plants and sample sites (Table 4). A notable exception to the ubiquity of these species was the absence of *Chaetomyar* sp. from samples of *V. reticulatum*. The major peaks in parasitism on *D. viscosa* were due to activity of *Polynema* spp., the most common parasitoids on this host plant (Fig. 1, Table 4). In contrast, total parasitism on *M. faya* fluctuated little over the year at three sites (Fig. 1) and appeared to consist mainly of *Schizophragma* and *Chaetomyar* (Table 4). However, a substantial proportion of parasitism (23% overall) was by un-

known parasitoids that emerged in the field before samples were collected (Tables 2 and 4), which cautions against concluding too much about the relative abundance of each species.

Because *S. rufofascia* prefers to oviposit in young foliage (Jones *et al.*, 2000), seasonal variation in plant growth is likely to result in shifting abundance on the various host plants. Seasonality in phenology of *D. viscosa* (M. T. Johnson, unpublished data) and *M. polymorpha* (Porter, 1973) may explain why parasitism on these hosts was so variable over our 1-year survey (Fig. 1). In contrast, *M. faya* may provide a steadier supply of host eggs due to its more uniform production of

TABLE 4

Effects of Host Plant and Site on Parasitism of *S. rufofascia* Eggs by Three Mymarid Species and Unknown Parasitoids

Effect	Level	% parasitism (mean across sample periods ± SE)			
		<i>Polynema</i> spp.	<i>Schizophragma</i> sp.	<i>Chaetomyar</i> sp.	Unknown parasitoids
Host plant	<i>Dodonaea viscosa</i>	6.1 ± 1.0	1.7 ± 0.5	1.5 ± 0.5	4.3 ± 0.8
	<i>Myrica faya</i>	0.7 ± 0.2	3.5 ± 0.6	2.8 ± 0.9	3.3 ± 0.6
	<i>Metrosideros polymorpha</i>	1.5 ± 0.4	2.0 ± 0.6	3.3 ± 1.3	1.9 ± 0.5
	<i>Vaccinium reticulatum</i>	1.4 ± 0.6	0.2 ± 0.1	0	0
	Kruskal-Wallis test				
	χ^2	27.72	14.86	6.83	19.38
	<i>df</i>	3	3	3	3
<i>P</i>	<0.0001	0.0019	0.0776	0.0002	
Site	Kipuka Kahalii (880 m)	2.9 ± 0.9	2.6 ± 0.9	6.4 ± 1.5	3.8 ± 0.9
	Puhimau Crater (1100 m)	1.9 ± 0.7	3.4 ± 0.7	2.3 ± 1.3	3.6 ± 0.8
	Devastation Trail (1130 m)	1.5 ± 0.4	2.4 ± 0.5	0.2 ± 0.1	3.5 ± 0.8
	Crater Rim (1160 m)	1.2 ± 0.5	0.6 ± 0.3	0.3 ± 0.2	0.1 ± 0.1
	Kipuka Puauulu (1190 m)	6.8 ± 1.8	0.3 ± 0.2	1.5 ± 0.6	1.7 ± 0.4
	Kruskal-Wallis test				
	χ^2	7.63	19.33	33.90	17.82
<i>df</i>	4	4	4	4	
<i>P</i>	0.1062	0.0007	<0.0001	0.0013	

leaves (Whiteaker and Gardner, 1987). Our survey method did not allow direct comparison of parasitism and leafhopper density; however, recent surveys in HAVO show that *S. rufofascia* densities are 3–10 times higher on *M. faya* than on adjacent *M. polymorpha*, and that densities on *M. polymorpha* are reduced up to 10-fold in areas where *M. faya* has been removed compared to nearby unmanaged areas (Lenz, 2000). These data indicate the importance of *M. faya* as a source of high populations of *S. rufofascia* as well as its parasitoids.

Of the three most common parasitoid species, *Chaetomyrmar* sp. is probably the most recent immigrant in Hawaii, and may have arrived simultaneously with *S. rufofascia*. The first record of this genus in Hawaii was in 1995 from *S. rufofascia* infesting guava on Kauai and *Cibotium splendens* Gaudichaud on Oahu (P. Yang, unpublished data). This parasitoid was not detected in 1995 samples of *S. rufofascia*-infested leaves from six host plants in HAVO, including the four plant species in the current survey (Yang *et al.*, 2000), which suggests that it has only recently moved into the park. The high level of parasitism by *Chaetomyrmar* sp. near sea level in Hilo (49%; Table 2) and the fact that parasitism by *Chaetomyrmar* sp. was highest at the lowest elevation in HAVO (Table 4) suggest that this species is spreading from low elevation habitats.

Yang *et al.* (2000) collected *Schizophragma* sp. probably *bicolor* in HAVO in 1995 from *S. rufofascia*-infested *M. faya*. This parasitoid was collected as early as 1963 in Honolulu and was probably introduced from North America (Huber, 1987). Its original host in Hawaii, prior to the introduction of *S. rufofascia*, is unknown.

In Hawaii, the cosmopolitan genus *Polynema* includes 14 described endemic species, perhaps 20 or more undescribed species (Beardsley and Huber, 2000), and 2 known introduced species (Nishida, 1994). The several morphospecies of *Polynema* collected in our survey are probably all endemic. Their native hosts are unknown, but presumably include some of the many endemic leafhoppers (Zimmerman, 1948). Our single most commonly collected morphospecies of *Polynema* also was collected in 1995 by Yang *et al.* (2000), along with two additional morphospecies that do not match specimens identified from the current survey. Thus a total of 5 to 7 endemic species appear to have adopted *S. rufofascia* as a new host, although one species is much more common than the rest. Parasitism by *Polynema* spp. was significantly higher on one host plant, *D. viscosa*, than others (Table 4), which suggests that the native host of one of these parasitoids may be associated with this plant. Further systematic and ecological studies of this genus should emphasize determining host associations. Although difficult to ob-

tain, this information will be of great assistance in assessing potential impacts of accidental and intentional insect introductions.

It remains to be seen whether natural enemies already present in Hawaii can suppress *S. rufofascia* populations to economically and ecologically acceptable levels. Parasitism rates observed in HAVO during this survey seem rather low, and indeed, sticky trap catches on *M. faya* show that leafhopper numbers have not declined in HAVO from 1994 (P. Yang and D. Foote, unpublished data) to 1999 (Lenz, 2000). However, the high rate of parasitism by *Chaetomyrmar* sp. in Hilo and its recent appearance in HAVO suggest that this species may become an important source of mortality in the future. We recommend continued monitoring in HAVO to determine if rates of parasitism increase with time.

Although Hawaii has a long tradition of biological control, with approximately 700 biological control agents introduced since 1900, the pace of introductions has slowed dramatically in the past two decades (Follett *et al.*, 2000). This slowdown is in part a result of increased concerns regarding the nontarget impacts of biological control agents, particularly on the large native Hawaiian flora and fauna (Howarth, 1991). Any introduction targeting control of *S. rufofascia* would therefore have to address the risk to native leafhoppers, such as the many species (> 62) in the endemic leafhopper genus *Nesophrosyne* Kirkaldy (Zimmerman, 1948). This task is extremely difficult because so little is known of the biology of native Hawaiian leafhoppers and of *S. rufofascia* in its native range. Thus, it appears fortunate that parasitoid species already present in Hawaii are able to attack eggs of *S. rufofascia*.

These parasitoids may obviate the need for a new introduction; however they themselves, in particular the nonnative *Chaetomyrmar* sp. and *Schizophragma* sp., have potential for negative impact on native leafhoppers. In addition to aiding movement of alien parasitoids into new areas, a successful invader such as *S. rufofascia* could elevate population levels of native as well as nonnative mymarids, shifting the balance to the detriment of already rare native leafhoppers (Settle and Wilson, 1990). The data from HAVO suggest that the threat to native leafhoppers may be particularly high in areas where parasitoids are dispersing from high populations of *S. rufofascia* on the weed *M. faya*.

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