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A Two-Year Survey of the Melon Aphid, *Aphis gossypii* Glover, on Crop Plants in Hawaii

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Abstract. Vegetable and flower farms on Hawaii and Kauai islands were surveyed over a two-year period to determine the distribution, abundance, phenology, and parasitoids of the melon aphid, *Aphis gossypii* Glover**.** Aphids were common on all crops sampled except luffa (*Luffa acutangula* L.). Populations were generally low (<2 aphids/cm^2) and were relatively stable at all sites, including wet (windward) and dry (leeward) locations. *Lysiphlebus testaceipes* Cresson was the most common parasitoid attacking the aphid, although it was not abundant and was hindered by high levels of hyperparasitism. Four new natural enemies of melon aphid are recorded for the first time in Hawaii: the newly introduced aphidiid parasitoid *Aphidius colemani* (Viereck); the fungal pathogen *Neozygites fresenii* (Nowakowski) Batko [Zygomycetes: Entomophthorales: Neozygitaceae]; the parasitoid wasp *Aphelinus varipes* (Foerster) [Hymenoptera: Aphelinidae]; and a parasitic fly, *Endaphis maculans* (Barnes) (Diptera: Cecidomyiidae).

No endemic or indigenous aphid species occur in the Hawaiian Islands; however, at least 79 species of aphids have been accidentally introduced and established from other regions around the world (Beardsley 1979, 1986; Ebesu et al. 1991; Rethwisch 1989; Russell 1982). Many of these invasive aphids have become serious pests of agricultural crops throughout the state, including *Brevicoryne brassicae* L. on cabbage, *Sipha flava* (Forbes) on sugarcane and pasture grasses, and *Myzus persicae* (Sulzer) on eggplant.

Among the most common of invasive aphid pests in Hawaii is the melon or cotton aphid, *Aphis gossypii* Glover, which attacks a large number of plant species, particularly in the family Cucurbitaceae. It is important both as a direct pest of crops and as a vector of viral pathogens, some of which can cause complete crop failure in certain situations. Johnson et al. (1989) reported melon aphid to be one of the major pests requiring suppression with insecticides on watermelon in Hawaii. It is a major vector of zucchini yellow mosaic virus, cucumber mosaic, watermelon mosaic 1 & 2, and several strains of the papaya ring spot virus (Cho et al. 1991, Ullman et al. 1991a). The latter disease was largely responsible for a 39% decline in papaya yield in Hawaii from 1993 to 1997, resulting in major statewide economic losses, as papaya is the fourth largest agricultural crop in the islands.

Mosaic viruses are non-persistent, and viral particles can be transmitted via a single probe of an aphid's mouthparts into a host plant. Therefore the distribution and abundance of aphids in the vicinity of infected crops, and especially the production of alate forms largely determine overall rates of crop infection (Ullman et al. 1991a).

Despite their economic importance, there has been little research conducted on the population dynamics of *A. gossypii* (or any other aphid species) in Hawaii. Johnson et al. 1989 reported that commercial watermelon plantings on Oahu and Molokai receiving regular insecticide applications had a season-long average of under 5 melon aphids/leaf, with occasional outbreaks to higher levels. In a study at Pulehu, Maui Island, Ullman et al. (1991b) reported that *A. gossypii* was the most abundant aphid in zucchini. Landing traps placed by

Ullman et al. (1991b) in Kula, Maui showed *A. gossypii* to be 1 of 4 aphid species (along with *Brevicoryne brassicae* L.*, Myzus persicae (Sulzer),* and *A. craccivora* Koch) to migrate into zucchini fields throughout the season, with *A gossypii* predominating in traps after the first harvest. Ebesu et al. (1991), again reporting on alate captures in pan traps, found *A. gossypii* to be the dominant aphid trapped outside zucchini fields at 3 sites on Maui, representing 16–26% of all alates recovered.

The importance of melon aphids in Hawaii as direct pests and as disease vectors suggests that a better understanding of their distribution and abundance may provide useful information that could lead to improved biological, cultural or chemical control. This is particularly true in light of studies showing that farm-level practices can lead to localized insecticide resistance in Hawaiian populations of *A. gossypii* (Hollingsworth et al. 1994). Population information may also be applicable to other sub-tropical Pacific Island ecosystems, such as Guam (Yudin et al. 1991), American Samoa (Ali & Vargo 1995), the Northern Mariannas (Quebral et al. 1991), and Micronesia (Schreiner 1991) where melon aphids also impact agricultural development.

As part of a classical biological control program designed to import *Aphidius colemani* (Viereck) and other parasitoids into Hawaii to contribute to aphid pest management, we sampled population levels of *A. gossypii* on a number of farms, primarily on the Big Island of Hawaii, over a 2-year period. In this paper, we present data on the relative population density of the aphid and its parasitoids on several crop species during this period. We also include information on another important pest in Hawaii, the banana aphid, *Pentalonia nigronervosa* Coquerel, which often occurred on the same plant species (red ginger, *Alpinia purpurata* (Vieill.)) along with *A. gossypii* during our field sampling. *P. nigronervosa* is the primary vector of banana bunchy-top virus, a major threat to the banana industry in Hawaii (Ferreira et al. 1997). Like *A. gossypii*, it is a suitable host and possible target for biological control with the imported parasitoid *A. colemani*.

Materials and Methods

Leaf disc samples. Aphid sampling on the Big Island was conducted from May 1997 to May 1999. Once each week at each site, a sample of 12 leaf discs was cut from each crop with a 2.9 cm diam. circular metal punch. Each disc was cut from a randomly chosen leaf in a plant patch without regard to size, age, or position (except for *A. purpurata* ; see methods described below). *A. gossypii* normally occurs on the underside of leaves, so cuts were made while observing the upper side to avoid visual bias. Using this method, apterous aphids were generally not disturbed, although some mobile alates dispersed and, thus, were not accurately sampled.

Leaf discs were transferred to 6-well plastic tissue-culture plates (Falcon no. 3046, Becton Dickinson Labware, Franklin Lakes, NJ), and transported in a cooled ice chest to the laboratory, where they were refrigerated (<24 h) at 5°C. until examined under a stereomicroscope. For each disc the following data were recorded: (A) number of immature apterous aphids (instars 1–2); (B) number of mature apterous aphids (instars 3–4, plus apterous adults); (C) number of alates; (D) number of aphids parasitized by aphidiids (brown mummies); and (E) number of aphids parasitized by aphelinid wasps (black mummies). Although it was not always possible to accurately distinguish between 2nd and 3rd instar apterae, the differentiation between immature and mature classes was used to approximate aphid population age structure. All mummified aphids were transferred individually into gelatin capsules and held in the laboratory until parasitoid emergence.

Except in a few cases where vegetation was sparse, leaf samples were taken from patches of ~50 m^2. Samples included as many of the following plant species as were available at

each site: cucumber *(Cucumis sativus* L.*)*, pumpkin and kabocha (*Cucurbita moschata* Duch.), zucchini *(Cucurbita pepo* L. var. *melopepo)*, luffa (*Luffa acutangula* L.*)*, choyote (= pipinella)*(Sechium edule (Jacq.))*, squash (*Cucurbita maxima* Duch.), pigeon pea *(Cajanus indicus* Spreng.*)*, eggplant (*Solanum melongena* L.*)*, taro *(Colocasia esculenta* L.*)*, red ginger *(Alpinia purpurata* (Vieill.))*, Hibiscus rosa-sinensis* L.*,* and watermelon (*Citrullus vulgaris* Schrad.)*.*

On red ginger, both *A. gossypii* and *P. nigronervosa* occur within the bracts at the apex of new shoots. These were sampled by cutting 2.9 cm of the shoot with the circular cutter. All overlapping bracts were included, thus resulting in a larger surface area than flat leaf discs. We estimated the number of aphids/cm^2 based on the area of the cutter (6.6 cm^2), but the average numbers of aphids in the ginger samples cannot be directly compared to leaf samples, since many more aphids can be sheltered within the bracts.

Samples were initially collected at 12 sites on the east side of the Big Island (Puna and Hamakua Districts). Fields were changed once a crop was harvested. If other crops were available at the same site, sampling was transferred to one of these; if no other crop was available at the site, the nearest location containing a suitable host crop was chosen. Sampling was continued at each location as long as host material was available, regardless of the size of aphid populations. Pesticide use (as reported by the growers) was rare at all except two of the sites. At Hilo Coast Co., diazinon was sprayed monthly. At Papaikou Site #2, herbicides were sprayed routinely on weeds, and vegetables were sprayed weekly with malathion.

Subsequently we added additional sites in the drier leeward south side of the Big Island. In the South Puna District, the Ka'u Growers Association (KGA) contains a number of farms (totaling about 600 ha) with various aphid host crops at 514–605 m elevation. Sampling in this area began in April 1998. At this time there was a drought, with little irrigation water available, so crops were sparse and short-lived and sampling was changed from one crop to another frequently. Subsequently, irrigation was introduced, and cropping became more regular.

Smaller samples were also collected at two sites on Kauai island: from May 14 to July 3, 1998 on taro leaves at the University of Hawaii Agricultural Research Center in Wailua**;** and from May 13 to June 12, 1998 on cucumber leaves at a small farm in the town of Anahola. Fig. 1 summarizes the overall temporal and spatial range of aphid sampling.

Whole leaf samples. At one site on the Big Island, 10 whole leaves of pumpkin or kabocha were randomly collected each week, simultaneously with leaf-discs, so the methods could be compared. The crop from which initial samples were collected at Smiley's Garden, Hilo eventually declined, so leaf sampling was moved to the Pepeekeo site, where it continued for the duration of the survey. At the Kauai Research center, 20 whole taro leaves/ week were sampled from May 7 to July 3, 1998 simultaneously with leaf-disc sampling.

The same data for whole leaves were recorded as for leaf-discs. and used to derive an estimate of aphids/cm^2 based on the surface area of each leaf. Because a leaf-area meter was not available, the area of cucurbit leaves was estimated as the product of midrib length by maximum leaf width. For taro, leaf area was estimated by multiplying the maximum leaf width by the distance from the tip to the end of a basal lobe.

Results and Discussion

The leaf disc sampling method provided a consistent, manageable, and fairly accurate index of overall aphid population density per square centimeter on whole leaves in both the kabocha and the taro fields that had simultaneous disc and leaf samples. As the data were non-normally distributed (Shapiro-Wilk test, W=.8982; P=.0067) we used non-parametric
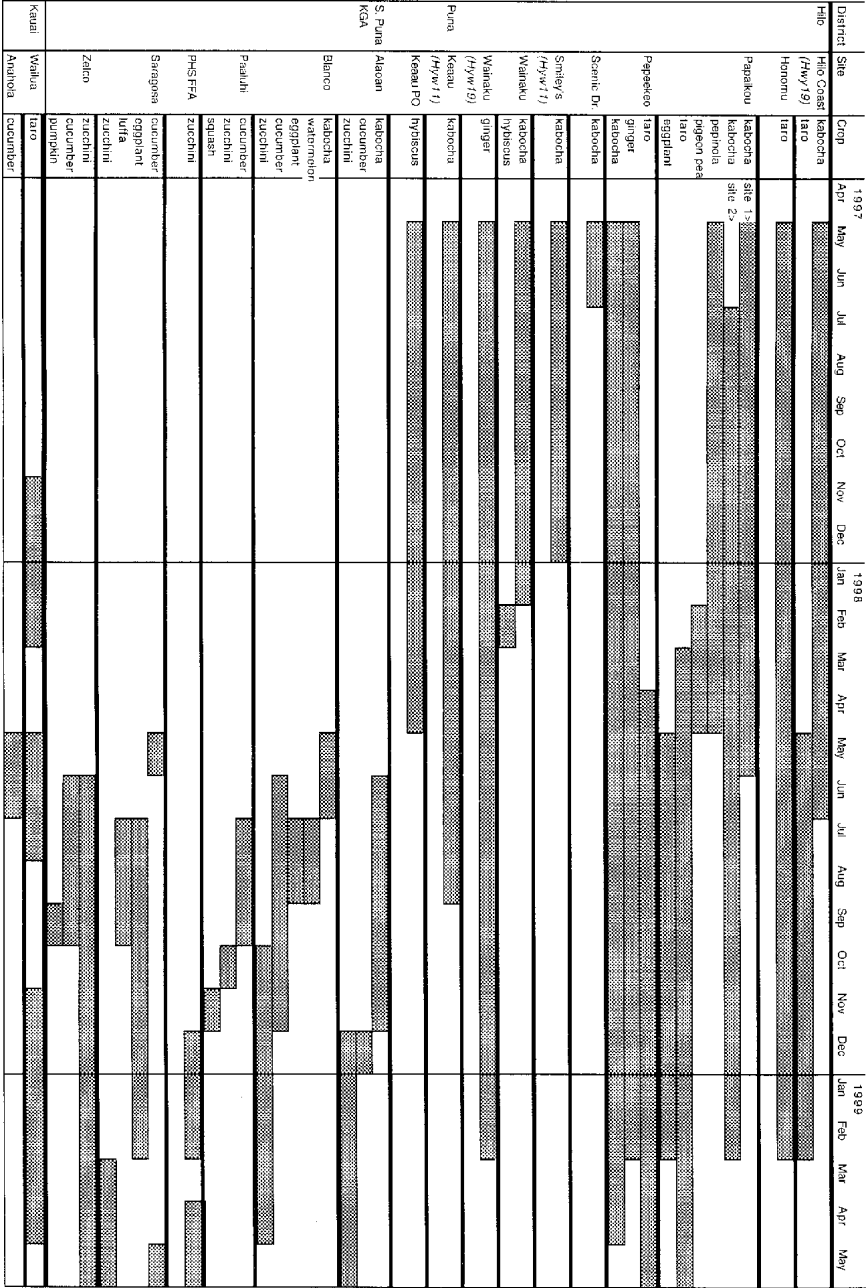
Figure 1. Spatial and temporal distribution of farm sites sampled during the two-year *Aphis gossypii* survey in Hawaii.
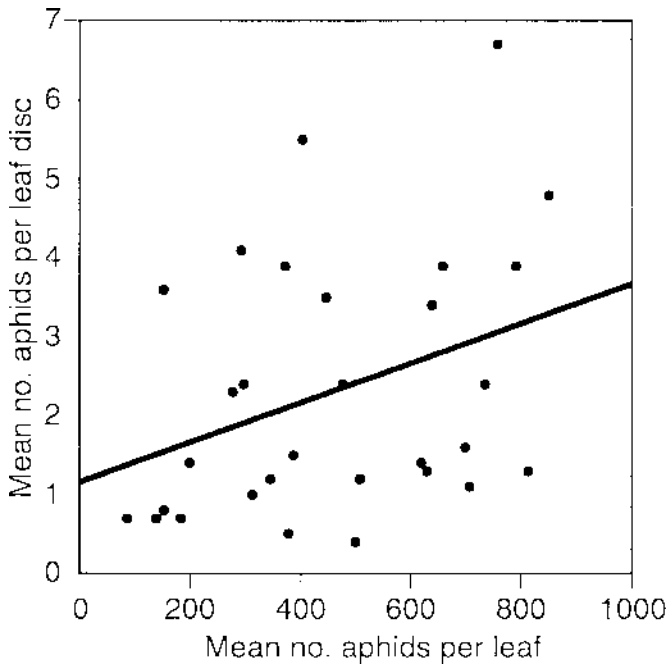
Figure 2. Number of aphids per leaf disc compared with number of aphiids per whole leaf in taro samples from Wailua Research Station, Kauai, Hawaii.

Spearman's rank correlations (R_s) to compare the mean number of aphids/cm^2 on discs and whole leaves for each sample date. Correlations for the 2 sites where kabocha was sampled on the island of Hawaii were highly significant ($R_s = 0.57$, P= 0.007, n = 21; and $R_s = 0.78$, P= 0.0001, n = 22). At the site on Kauai were taro was sampled, the correlation between whole leaf and disc counts was again significant ($R_s = 0.42$; P= 0.0180; n = 31) (Fig. 2).

At sites that were sampled continuously over long periods of time, *A. gossypii* population densities were generally moderate and relatively stable. As an example, Fig. 3 shows data from the Papaikou site, centrally located in the Hamakua Coast area on the windward side of the Big Island. Despite vagaries of weather, plant phenology, plant quality and natural enemies, population density consistently remained within the range of 0.01 to 1.6 aphids/cm^2 over the entire 2-yr survey period.

At the Hamakua (windward, high moisture) sites, average *A. gossypii* densities averaged across all crops ranged between 0.5 and 1.0 aphids/cm^2 during the spring and summer months and 0–0.5 aphids/cm^2 during winter months. At the Ka'u (leeward, drier) sites, average densities were highest (1.0–1.5 aphids/cm^2) during early autumn. There was no evidence of sharp population peaks and crashes with 100 fold changes in population density as sometimes seen on mainland crops (Layton et al. 1999). Other than red ginger (where aphids/cm^2 could not be accurately calculated due to multiple overlapping bracts), there were only 3 samples out of a total of 7,800 in which aphid densities exceeded 10/cm^2, (2 on taro and 1 on kabocha); and only 20 samples (0.2%) with >5 aphids/cm^2.
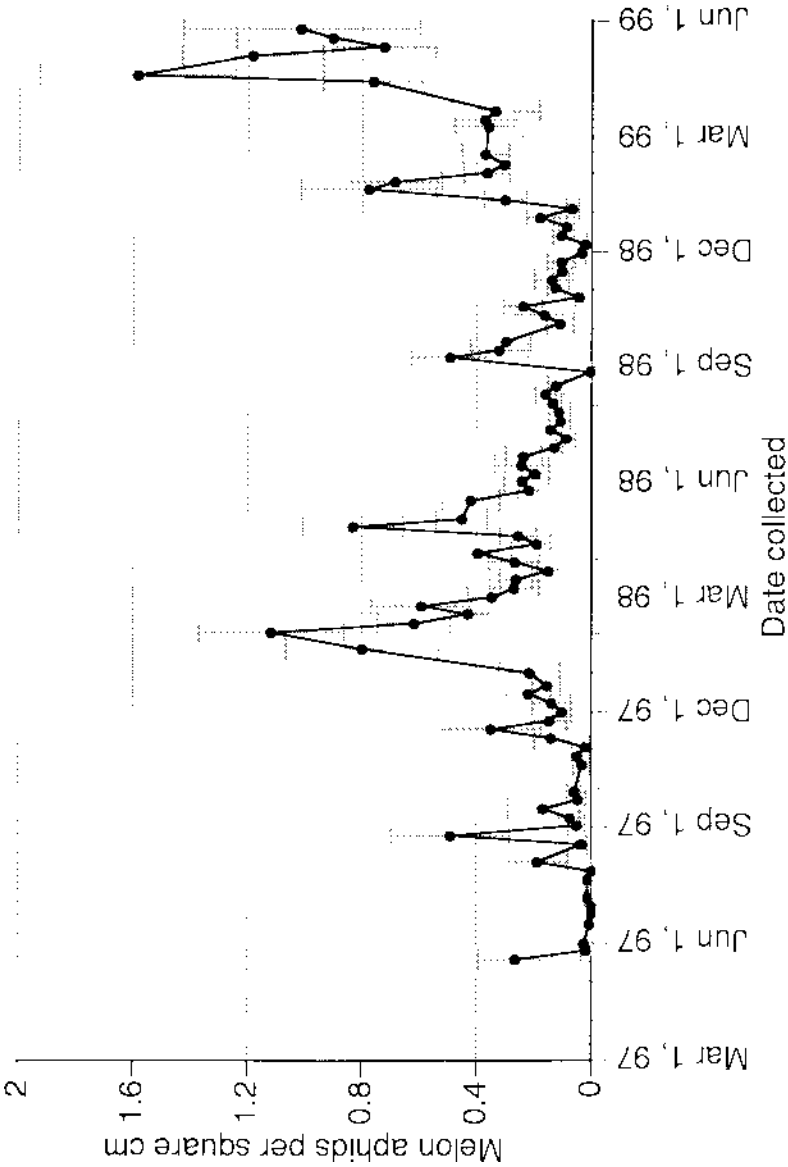
Figure 3. Mean number of melon aphids/cm^2 of leaf tissue from the Papaikou site, located in the Hamakua Coast area on the windward side of the Big Island.
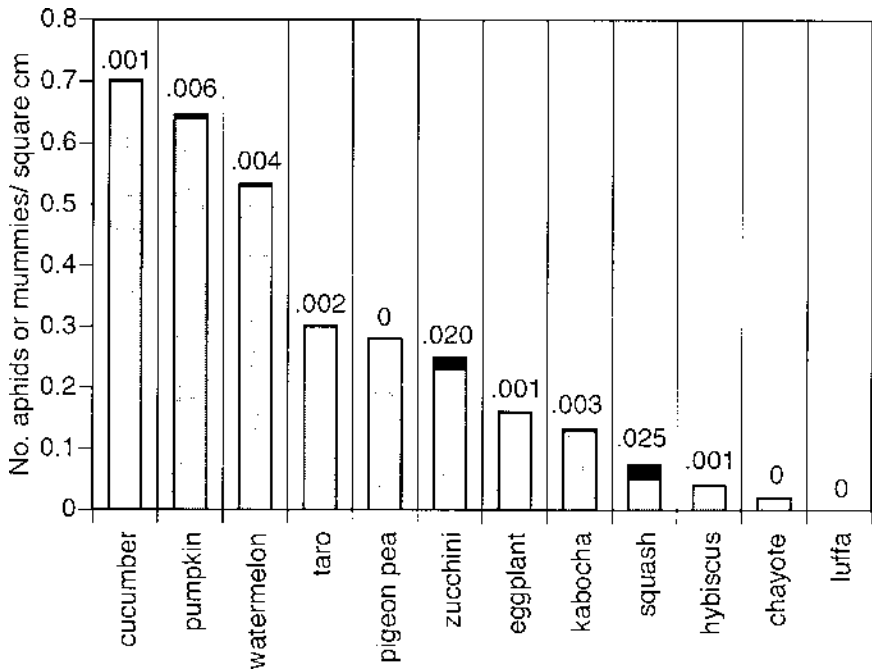
Figure 4. Mean number of melon aphids and mummies/cm^2/sample date on each of 11 host plants in Hawaii. Light (lower) portion of each bar represents aphids; dark (upper) portion represents mummies. Actual means, presented above each bar, represent total mummies collected containing *L. testaceipes, A. colemani*, or hyperparasites.

Although the Hamakua area receives on average 381 cm of rain per year, while the Ka'u area receives only 127 cm per year (Atlas of Hawaii, 1983), there were no corresponding major differences in the population densities of melon aphids on any of the crops in the two regions. On Kauai, the cucumber field in Anahola had an average of 1.6 aphids/cm^2, while the Wailua taro field had an average of 2.4 aphids/cm^2.

Only luffa, of the crop plants sampled, never yielded a single specimen of *A. gossypii*; all others contained some level of melon aphid infestation. Red ginger consistently had the highest number of melon aphids per sample (though numbers could not be compared directly with other crops). There were highly significant differences in melon aphid abundance among the remaining crops (ANOVA: F= 19.99, P= 0.0001), ranging from 0.02 aphids/cm^2 of leaf area per sample date for chayote to 0.70 aphids/cm^2 for cucumber (Fig. 4).

Smaller apterae (1st and 2nd instars) comprised 70–100% of the melon aphid population across all samples. During the entire 2-yr survey only 139 alates were collected in the disc samples. The sampling method probably disturbed and displaced some alate individuals; nevertheless, the low percentage of winged aphids seen in the field suggests that alate production is generally low, consistant with the low overall population densities. The whole leaf samples also had a low percentage of alates (total of 48 winged aphids on 1,049 leaves).

Alate production is a complex function of population density, host quality and environmental variables. In California, *A. gossypii* on cotton tends to form alates during mid-season when densities exceed 32 aphids/cotton leaf (Godfrey & Rosenheim 1996). There are no comparable data available to quantify the relationship of these factors to alate production in Hawaiian ecosystems. Although our data show generally moderate densities of aphids, the ability of even few alates to vector substantial disease loads means that aphid control remains a priority for cucurbit farmers. As *A. gossypii* becomes increasingly resistant to chemical insecticides applied on a local level (Hollingsworth et al. 1994), management of aphid populations in Hawaii may require an area-wide approach that uses biological and cultural methods, and coordination of planting and harvesting schedules. Although we collected relatively few alates, losses in cucurbit crops in Hawaii due to disease are substantial (Ullman et al. 1991).

Of the crop plants surveyed, only red ginger contained populations of the banana aphid (*P. nigronervosa).* Banana aphids were often found infesting flower bracts simultaneously with melon aphids in mixed colonies. Population densities of banana aphid were slightly higher than those of melon aphid, with a mean of 4.3 ± 1.1 *P. nigronervosa* per red ginger sample, compared to 3.6 ± 1.9 *A. gossypii* per sample.

P. nigronervosa is an important vector in Hawaii of the banana bunchy-top virus, a serious disease that was previously confined to Oahu, but has since spread to Kauai and the Big Island and is threatening the banana industry (Ferreira et al. 1997). Although the virus only infects bananas in Hawaii, it is persistent in the aphid (Brunt et al. 1997). Therefore, an infected alate may migrate to an alternate host such as red ginger, but retain its ability to transmit the disease. In Hawaii, cut flowers such as red ginger are frequently transported around the islands, and while banana plants are quarantined, other hosts of *P. nigronervosa* are not. Red ginger is often planted in close proximity to areas where diseased bananas occur (e.g. home gardens, small orchards and farms). Therefore, infected aphids could possibly move from banana to red ginger and be transported with cut flowers, and subsequently return to another banana host.

The few farms in our study that used insecticides on a regular basis had generally lower but recurring populations of aphids. Previous work by Johnson et al. (1989) showed that insecticide use could lead to localized aphid outbreaks, presumably due to natural enemy mortality. At the Hilo Coast Site, sprayed regularly with diazinon, populations remained below 0.2 melon aphids/cm^2 in almost every sample. However, there were several population outbreaks: in May 1998 densities reached 2.6 aphids/cm^2 and in Sept. 1998 reached 4.2 aphids/cm^2, one of the highest levels observed in the survey.

Prior to the introduction into Hawaii of *Aphidius colemani*, accomplished in 1999 during the course of this study (R.M., unpublished), only one other aphidiid parasitoid that attacks *A. gossypii* was established in the state. *Lysiphlebus testaceipes* (Cresson), a generalist attacking many aphid species, was introduced to Hawaii in 1923 from California (Beardsley 1961). Based on recovery of mummies in this study, *L. testaceipes* is widespread, but appears to attack *A. gossypii* at relatively low levels (generally less than 1 mummy recovered per 10–100 aphids). *Aphidius gifuensis* Ashmead and *Diarettiella rapae* (Ashmead) are listed as possible parasites of melon aphid by Mackauer & Stary (1961), but are not so listed by Stary & Schlinger (1967) in their revision of the Asian aphidiids, nor by Beardsley (1961) for the Hawaiian records, and were not detected during this survey. Of the *A. gossypii* mummies that we collected, 282 *L. testasceipes* and 250 *A. colemani* emerged. More than twice as many hyperparasites (1,227) as primary parasites (532) were recovered overall.

The only other parasitoid occurring regularly (if infrequently) in our samples was the aphelinid species *Aphelinus gossypii* Timberlake. It was most often found in taro (total of 20 mummies) and rarely in other crops (total of 9 mummies).

Because insect parasitoids often choose their hosts based in part on host-habitat, we examined the distribution of parasitoid mummies as well as aphids across host plants to determine if parasitoids showed preference or avoidance for particular crop species. No parasitoids were recovered from chayote, pigeon pea or luffa, while maximum abundance was 0.025 mummies/cm^2 on squash. Although squash had a relatively low abundance of aphids overall (Fig. 4), the ratio of parasitoids/aphids was highest on this crop. Conversely, red ginger had a relatively high density of melon aphids, but the proportion of these aphids parasitized was quite low, presumably because aphids were protected beneath the flower bracts. If the recently introduced parasitoid *A. colemani* becomes more widely established throughout the islands, it may increase parasitism levels of *A. gossypii* in red ginger, as it has been shown to be more effective than other parasitoids in searching for aphids in concealed locations (Stadler & Volkl 1991).

Besides the above-mentioned parasitoids, our survey detected several additional aphid natural enemies in Hawaii that have not previously been recorded in the literature. The fungal pathogen *Neozygites fresenii* (Nowakowski) Batko (Zygomycetes: Entomophthorales: Neozygitaceae) was found infecting *A. gossypii* on taro plants grown in the field on Kauai, as well as on cucurbit plants grown in a greenhouse. At times, this fungus caused severe and dramatic epizootics, virtually eliminating dense aphid populations from entire crop plantings. *N. fresenii* is a widely known pathogen that has previously been recorded from *A. gossypii* and other aphids on the U.S. mainland (Steinkraus et al. 1995), but this appears to be the first record of its occurrence in Hawaii (Donald Steinkraus, Univ. of Arkansas, pers. comm). On red ginger, a Dipteran parasitoid was observed to cause high levels of mortality in the banana aphid, even among aphids completely enclosed within tight bracts of the red ginger shoots. A collection on Kauai of *P. nigronervosa* cohorts on red ginger adjacent to banana plants yielded parasitism rates at times >50%. The parasite was also dissected from *A. gossypii* on red ginger on Kauai. The fly has been identified as *Endaphis maculans* (Barnes) (Cecidomyidae), which has previously been documented as attacking banana aphids in Trinidad (Kirkpatrick 1954); as well as *A. gossypii*, *Aphis spiraecola* Patch, and *Toxoptera aurantii* (Boyer de Fonscolombe) in Florida (Tang et al. 1994). This is the first record of its occurrence in Hawaii… an example of fortuitous biocontrol.

We also reared *Aphelinus varipes* (Foerster) (Hymenoptera: Aphelinidae) from *A. gossypii* on taro at Honomu on the Big Island of Hawaii. Its occurrence was quite rare. The Hawaii Dept. of Agriculture previously undertook a project to import *A. varipes* from the USDA-ARS Laboratory in Delaware for aphid biological control, but the best available records indicate that the species was never released from quarantine. Thus, this appears to be another fortuitous, accidental introduction of an aphid parasitoid from an unknown source, and is another new state record.

These 3 inadvertently introduced natural enemies, along with previous deliberately introduced predators and parasitoids, and the newly established *A. colemani* combine to form a complex of natural enemies that help exert a strong dampening influence on potentially explosive aphid infestations on important crops throughout the Hawaiian Islands. The efficacy of Hymenopterous parasitoids attacking aphids in the state is impacted by abundant hyperparasites that are also widely distributed in the islands. During the course of our survey, we reared 3 hyperparasitic Hymenoptera: *Pachyneuron siphonophorae* (Ashmead) (Pteromalidae); *Syrphophagous aphidivorous* (Ashmead) and *Syrphophagous* sp. (Encyrtidae) from primary aphid parasitoids developing in *A. gossypii*. At times, the rate of hyperparasitism reached >95% on aphidiids attacking melon aphid on greenhouse cucumber and field taro. Nevertheless, the combination of parasitoids, predators, pathogens and abiotic factors (wind and rain) combine to maintain aphid populations at relatively low levels.

Although it is generally assumed that aphids which transmit viruses are difficult to control using natural enemies, there are some indications that biological control may be able to contribute to disease management. Landis & van der Werf (1997), using exclusion studies, showed that predators attacking aphid populations in sugar beets could reduce infection rates of beet yellows virus by 30%. Likewise, the introduction of *Aphidius salicis* Haliday into Australia for biocontrol of carrot aphids, *Cavariella aegopodii* (Scopoli), led to a reduction in the incidence of carrot motley disease (Huffaker & Messenger 1976). It is usually alate aphids which vector viral disease, and as alates are often generated as a response to overcrowding, any reductions in area-wide aphid population densities should lead to lower rates of alate production and lower rates of disease spread (Wellings 1991). It would therefore be advantageous to introduce additional aphid natural enemies to the Hawaiian Islands to further reduce A. *gossypii* populations on crops and non-crop host plants.

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