Abundance and Seasonal Occurrence of Pest Fruit Flies (Diptera: Tephritidae) in Residential and Rural Areas of Oahu (Hawaiian Islands)

Luc Leblanc[1], Steven Graham[2], Steve McNeil[2], Kurt Pohlman[2], Michael Dinneen[2], and **Brian Fujita[2]**

[1]Department of Plant and Environmental Protection Sciences, University of Hawaii, 3050 Maile Way, Room 310, Honolulu, HI 96822-2271. [2]USDA-APHIS, 41-650 Ahiki Street, Waimanalo, HI 96795

Abstract. A trapping network is maintained on Oahu (Hawaiian Islands) for early detection of invading fruit flies. The 359 sites are concentrated around the main ports of entry in the south, the community gardens throughout the island, and the commercial farming areas in Waialua and northeast Oahu. Data on abundance and seasonal fluctuation cycles, based on five years (2009-2013) of male lure and protein trapping data, are presented for three species of pest fruit flies, *Bactrocera cucurbitae* (Coquillett), *B. dorsalis* (Hendel) and *Ceratitis capitata* (Wiedemann). Over 87,000 samples yielded 8.5 million flies of the four established species (54.9% *B. dorsalis*, 43.7% *B. cucurbitae*, 1.4% *C. capitata*, plus a few *B. latifrons* (Hendel)). No new invading species were collected. Trap captures for all three species were highest during summer months each year, with secondary peaks for *B. cucurbitae* later in the year in rural areas of southern Oahu, related to cucurbit host commercial production. At one site, with coffee in cultivation, *C. capitata* peaked between October and December. Seasonal cycles of *B. dorsalis* and *C. capitata* in residential areas appeared to be determined by the fruiting of ornamental trees and shrubs, including mango, rather than guava for *B. dorsalis* or coffee for *C. capitata*. The high correlation between captures of males in male lure traps and females in protein traps for the three species suggests that both attractants can be used to monitor seasonal abundance.

Key words: *Bactrocera*, *capitata*, *Ceratitis*, *cucurbitae*, *dorsalis*, food lures, *latifrons*, male lures, trapping

Introduction

The diverse dipteran family Tephritidae includes numerous pest species that damage fruits and fleshy vegetables. Four of the most destructive species are established in Hawaii and cause severe damage to crops: the polyphagous Mediterranean fruit fly (*Ceratitis capitata* (Wiedemann)) and Oriental fruit fly (*Bactrocera dorsalis* (Hendel)), the oligophagous melon fly (*B. cucurbitae* (Coquillett)), primarily associated with Cucurbitaceae, and Malaysian fruit fly (*B. latifrons* (Hendel)), specialized on Solanaceae. These four species have been detected repeatedly in surveillance traps in California, since the initial detection of melon fly in that state in 1956 (Papadopoulos et al. 2013). At least some of these invasions likely originated from Hawaii (Barr et al. 2014).

A trapping program was initiated on Oahu in early 2006, covering 40 sites, to confirm that no additional species were established (Leblanc et al. 2012). The trapping network was re-organized in 2009 into an early detection network for invasive species, with numerous sites around ports of entry and other high-risk areas. Results from the first three years of trapping were published before, with emphasis on spatial distribution trends (Leblanc et al. 2012). Here, we summarize the wealth of data generated during the subsequent five years of continuous trapping (2009-2013), presenting detailed comparisons of trap captures by individual site and habitat and characterizing the trends in seasonal abundance of each species as they relate to the local availability of host fruit.

Materials and Methods

The trapping network covered in this paper has been maintained continuously since April 2009 on Oahu with 359 sites (Figs 1 and 3–8), with bucket traps baited with male lures and multilure traps baited with the food attractant torula yeast. Bucket traps were made of one-liter white polyethylene containers (Highland Plastics, Mira Loma, CA), with four lateral 22-mm-diameter holes, 24 mm below the top to allow fly entry, and five small drainage holes at the bottom to prevent water accumulation. The trap was attached to a support tree with a 15-guage aluminum tie wire, inserted through a central hole in the lid fitted on the trap top, and bent into a hook inside the trap. For each of three traps, male lure plugs charged with 2 g of cue-lure (attracts *B. cucurbitae*), methyl eugenol (attracts *B. dorsalis*), or trimedlure (attracts *C. capitata*) (Scentry Biologicals, Billings, MT) were placed inside a plastic basket (AgriSense, Palo Alto, CA), suspended from the trap's ceiling through the wire hook. One 25x90-mm strip containing 10% dichlorvos (Vaportape, Hercon Environmentals, Emingsville, PA) was also attached to each trap's hook to rapidly kill the flies entering all bucket traps. A MultiLure trap (Better World Manufacturing, Fresno, CA), consisting of a transparent cover that interlocks with an opaque yellow base, allowing insect entry through a bottom opening and serving as a vessel to hold liquid, was used with five torula yeast pellets (ERA International, Freeport, NY), diluted in 400 ml of water. Traps were placed on host plants, whenever available, with the cue-lure and trimedlure traps on one tree, at least 2 m apart, and the two other traps on another tree, at least 3 m distant from the first tree.

To determine placement of sites, the island was divided into a grid of 1-square-mile (2.59-km^2) cells, and trapping sites were assigned to selected cells at varying densities. Most sites were located on southern Oahu, from Diamond Head to Ewa Beach, with at least two sites per cell grid maintained at any time. Traps were also set up in the two rural regions with a high concentration of small-scale commercial farming, in Waialua (11 sites) and Northeast Oahu (Laie and Kahuku) (7 sites), with two sites per grid cell. In addition, one set of traps was placed at each of the 11 community gardens, throughout the island, and at the Waimanalo Gulch sanitary landfill. Of the 359 sites, 235 contained four traps, baited with cue-lure, methyl eugenol, trimedlure and torula yeast (Figs 3a, 5a, 7a). The other 124 sites, nearest (up to 0.5 mile) to the ports of entry, contained only torula yeast traps (all sites on Figs 4a, 6a, 8a, that are not displayed on Figs 3a, 5a, and 7a). All the sites in Northeast Oahu, Waialua, the community gardens and the landfill contained all four attractants.

Sixty-five sites (45 with all lures and 20 with protein only), including the community gardens, the landfill, northeast Oahu and Waialua, were static, maintained continuously over the five years of trapping. The remaining 294 sites (190 with all lures and 104 with protein only) were rotation sites, with traps moved every three months to the next of four sites within a grid cell. At any time, at least two active trapping sites were present within a 1-mi^2-grid cell. As a result, a mean number of 123.4 ± 21.7 (SD) sites was serviced every week (79.4 ± 13.8 sites with all lures and 44.0 ± 8.7 with protein only).

Traps were emptied weekly, with torula yeast pellets and water replaced weekly in the protein traps and lure plugs and pesticide strips replaced every eight weeks in the bucket traps. Trapped flies were carefully examined by technicians to ensure that none other than the four established species were present in samples. Any suspicious fly was set aside and handed to the lead author for further identification. All flies were counted and sexed for the protein trap samples. For male lure trap samples, all flies were counted for samples ≤ 10-ml in volume. For larger samples, flies in a 10-ml sample were counted, and the total number was estimated by measuring volume of the entire sample. Ten ml of dry male flies contained 90 ± 13 (SD) (n=464) *B. cucurbitae*, 106 ± 13 (n=1120) *B. dorsalis*, and 264 ± 46 (n=12) *C. capitata*.

For analysis, site habitat was classified as residential (225 sites), rural (42 sites, including northeast Oahu and Waialua) or urban (63 sites) based on ground examination and plotting site coordinates on Google Earth. Residential sites were in neighborhoods dominated by single family bungalows, with a diversity of backyard fruit trees and frequently small vegetable gardens. Urban sites were dominated by larger residence buildings and/or commercial or industrial buildings, and fruit fly host plants were sparsely available. Rural sites contained small to large-scale commercial agriculture plots, as vegetable farms and/or papaya or mango orchards. The community gardens, generally embedded in residential areas, were analyzed separately because of the higher concentration of cultivated host material. Because of their isolation in three distinct geographic areas, rural sites were analyzed separately as rural south, Waialua and northeast Oahu sites (Fig. 1). A small number (18) of sites could not clearly be assigned to a habitat category and were excluded from the habitat comparisons and seasonal abundance graphs. Detailed trap locations and their surrounding habitat are visible on satellite photographs in the supplementary online material file (http://hdl.handle.net/10125/25001). The Quantum GIS software (www.qgis.org) was used to generate maps with mean density of trapped flies at each site. All data are presented as mean number of male (male lure traps) or female (protein traps) flies per trap per week. To compare captures in different habitats, data were LOG_{10} (x+1) transformed to reduce variance and analyzed using one-way ANOVA (SAS Institute 2004). Means were compared using the Tukey's honest significant difference test. The seasonal abundance graphs are presented as mean monthly captures for all sites covering each habitat. One site, with coffee cultivation, was treated separately from the other rural sites in southern Oahu for the *C. capitata* data.

Results

A total of 87,210 samples were collected and processed during the five years of trapping, yielding 3.7 million *B. cucurbitae*, 4.6 million *B. dorsalis*, 0.12 million *C. capitata*, and 114 *B. latifrons* (Table 1). Protein trap samples were frequently male-biased for *B. cucurbitae* (overall 1.6 male per female) and *B. dorsalis* (1.3 male per female) and female biased (1.7 female per male) for *C. capitata* (Table 1).

Table 1. Number of samples and flies collected for each of the four lure traps on Oahu between 2009 and 2013. Data used for analysis and graphs are in bold characters.

Lures		**Cue-lure**	**Methyl eugenol**	**Trimedlure**	**Protein**
Number of samples		19,148	19,148	19,148	9,766
Number of flies					
B. cucurbitae	males	**3,382,379**	278	180	191,653
	females	213	30	20	**121,376**
B. dorsalis	males	121	**4,473,799**	201	95,261
	females	10	358	17	**72,981**
C. capitata	males	10	16	**104,841**	5,908
	females	1	1	58	**10,234**
B. latifrons	males	1	0	2	64
	females	0	0	0	47

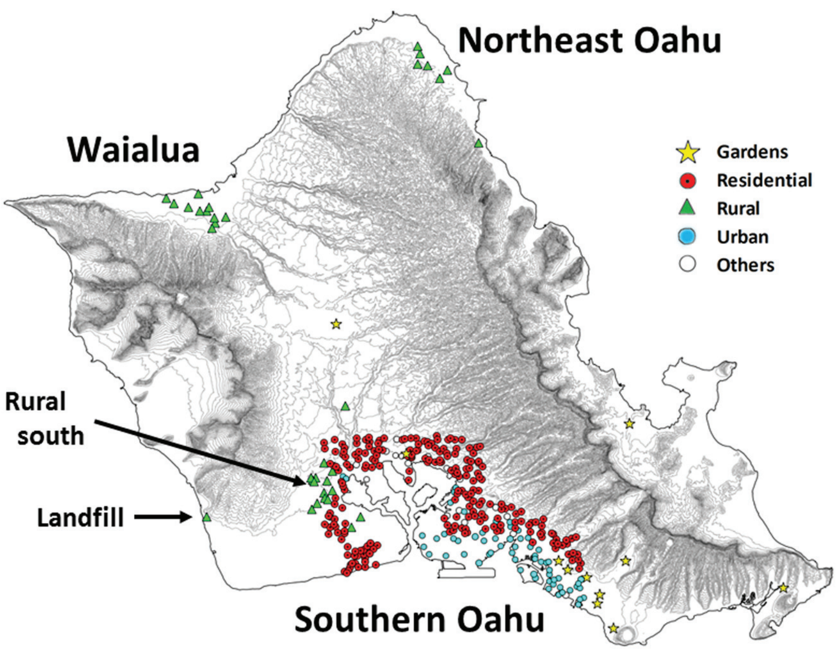

Figure 1. Map of trapping sites on Oahu (2009–2013), with habitat at each site.

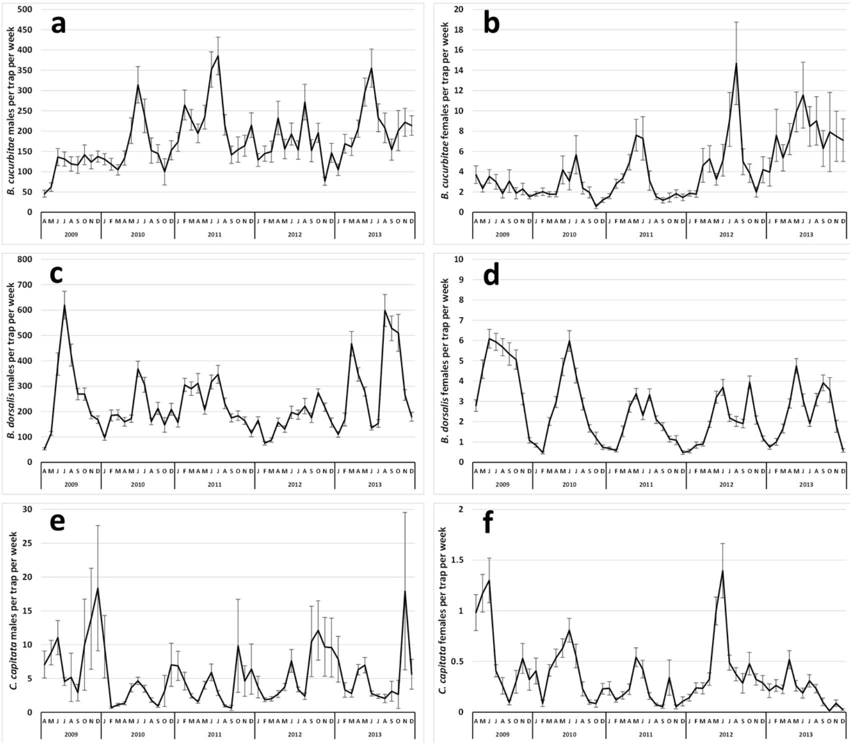

Figure 2a–f. Overall mean (±SE) monthly captures of male *B. cucurbitae* in cue-lure traps (a), female *B. cucurbitae* in protein traps (b), male *B. dorsalis* in methyl eugenol traps (c), female *B. dorsalis* in protein traps (d), male *C. capitata* in trimedlure traps (e), and female *C. capitata* in protein traps, based on all trapping sites maintained on Oahu between April 2009 and December 2013.

Because these ratios may be influenced in part by lure contamination or the proximity of male lure traps, only female capture data were used for protein trap capture data analysis.

Only the four established species were observed in the samples, by the USDA-APHIS co-authors, who collected and counted the flies, or by the lead author, who regularly contributed time to help processing samples and provided training sessions to the technicians on species diversity and identification. Genetic sequencing of over 900 specimens of *B. dorsalis* showed genetic uniformity, consistent with the Asian populations of that species (San Jose et al. 2013, Barr et al. 2014). However, the remote possibility that a few specimens of another cryptic species in the *B. dorsalis* complex may have been missed in the sorting cannot be entirely ruled out (Leblanc et al. 2012).

Mean monthly trap capture graphs, for all sites combined (Fig. 2) or pooled by habitat (Figs 3–8), all showed clear and repeated seasonal fluctuation patterns, discussed below. Graphs for the individual sites for which trapping was maintained continuously are available in the supplementary online material file (http://hdl.

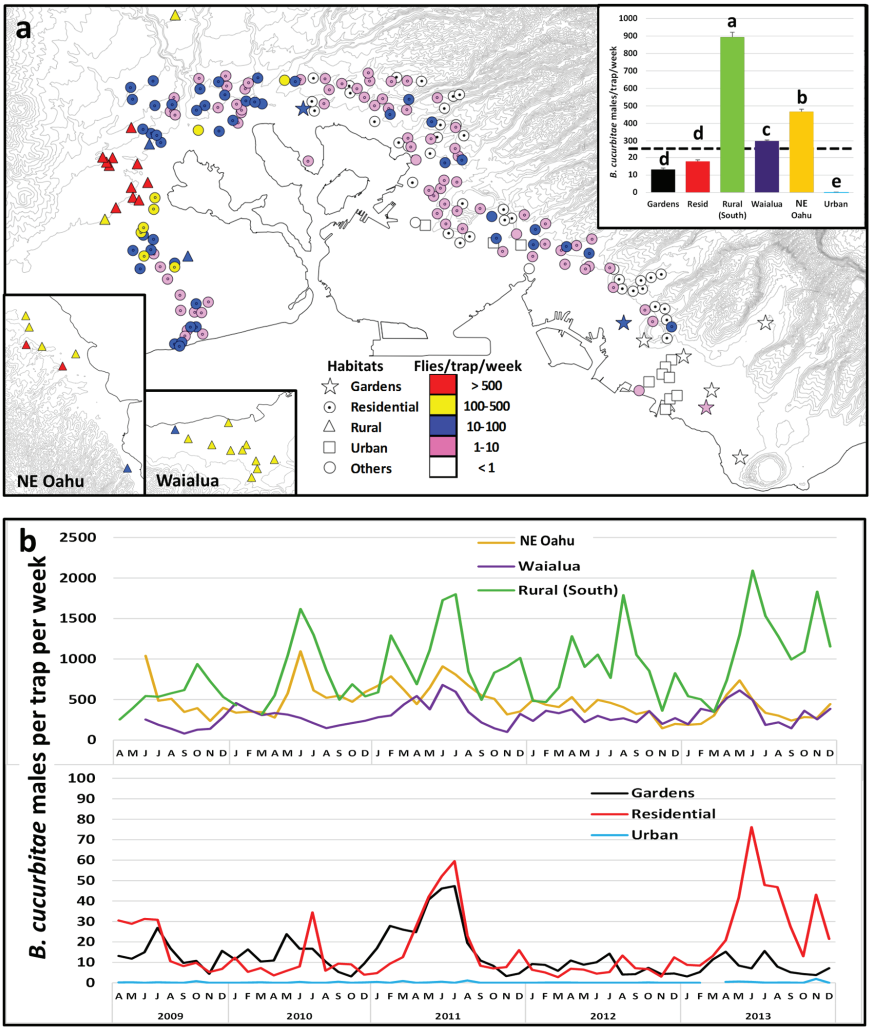

Figure 3a–b. Mean captures of male *B. cucurbitae* per trap per week in cue-lure traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). F = 5453.02; df = 5,18128; $P < 0.001$; $r^2 = 60.06\%$); n = 2514 (gardens), 1807 (NW Oahu), 8879 (residential), 1720 (rural), 739 (urban), 2475 (Waialua).

handle.net/10125/25001). Analysis of variance showed that trap captures were significantly ($P < 0.05$) influenced by habitat for males and females of all three species (see footnotes of Figs 3-8). Effect of seasonality (monthly captures) was also significant ($P < 0.05$) for all species in all habitats, except for male *B. cucurbitae* in urban sites ($F_{54,684} = 0.93$, $P = 0.620$, $r^2 = 6.83\%$) and female *C. capitata* in Waialua

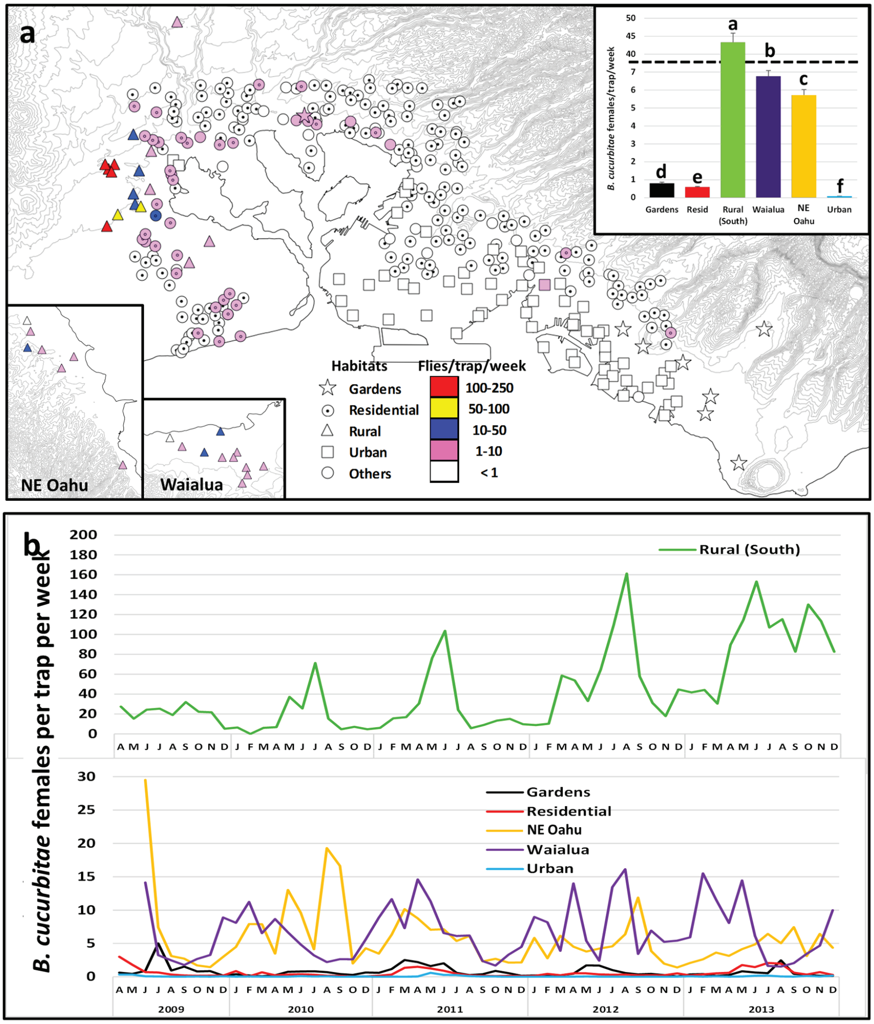

Figure 4a–b. Mean captures of female *B. cucurbitae* per trap per week in torula yeast traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). $F = 2897.68$; df = 5,27536; $P < 0.001$; $r^2 = 34.48\%$; n = 2514 (gardens), 1807 (NW Oahu), 13230 (residential), 1886 (rural), 5630 (urban), 2475 (Waialua).

($F_{54,2420} = 1.10$, $P = 0.283$, $r^2 = 2.40\%$) and Northeast Oahu ($F_{54,1745} = 1.09$, $P = 0.310$, $r^2 = 3.26\%$).

Melon fly was by far most numerous, in cue-lure and protein traps, in the rural areas of southern Oahu but was also abundant in northeast Oahu and Waialua. It was much less common in community gardens and residential areas and was rare or absent in urban sites (Figs 3a, 4a).

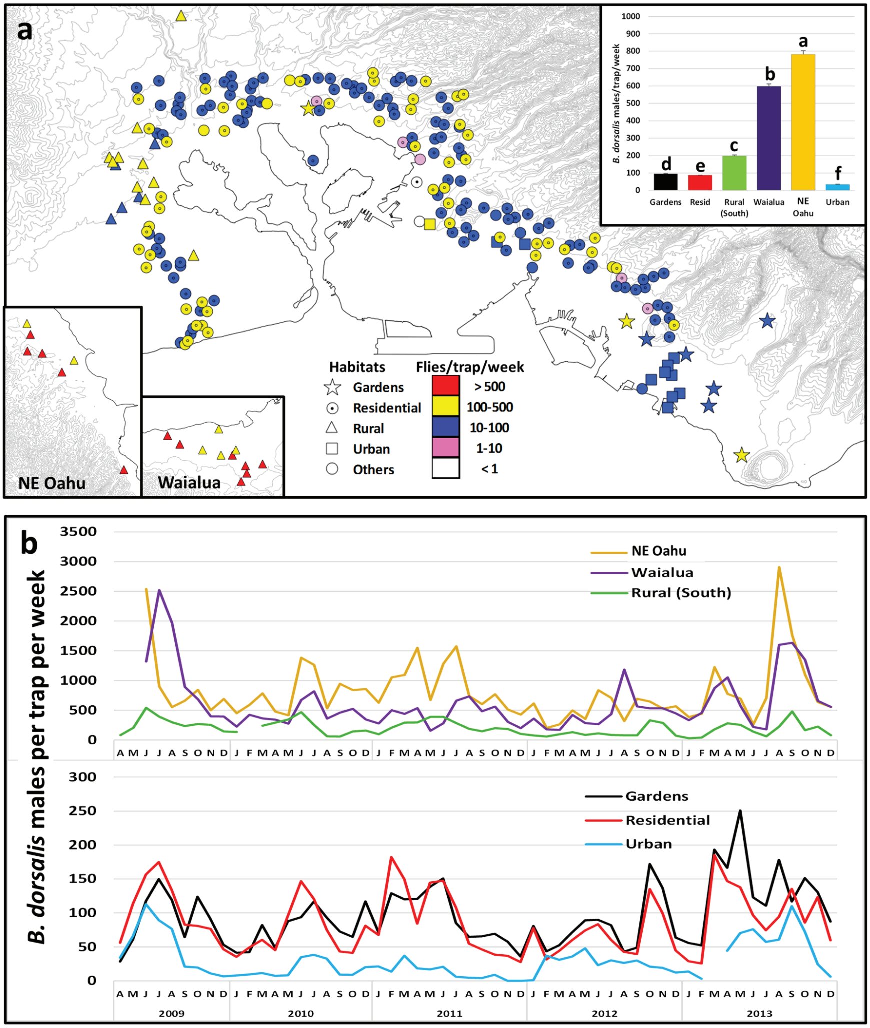

Figure 5a–b. Mean captures of male *B. dorsalis* per trap per week in methyl eugenol traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). $F = 1459.54$; df = 5,18128; $P < 0.001$; $r^2 = 28.70\%$; n = 2514 (gardens), 1807 (NW Oahu), 8879 (residential), 1720 (rural), 739 (urban), 2475 (Waialua).

Peaks in cue-lure trap captures occurred during the summer every year, generally between June and August (Fig. 2a), and the peaks were most pronounced in the rural south, community gardens, and residential areas (Fig. 3b). Fly captures in cue-lure remained high throughout the year in the three rural regions, with additional peaks in the rural south region in the last months (October to December) of 2009, 2011, 2012 and 2013, and in February 2011 (Fig. 3b). Peaks were observed during summer

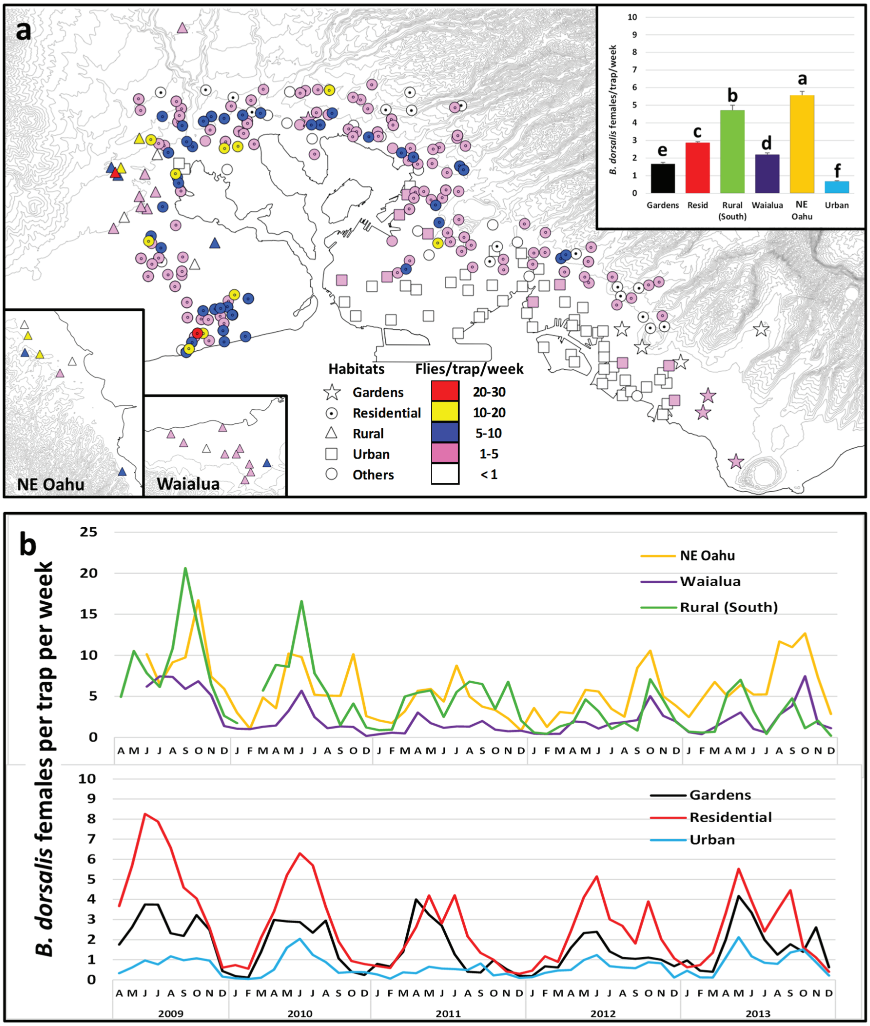

Figure 6a–b. Mean captures of female *B. dorsalis* per trap per week in torula yeast traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). $F = 447.43$; df = 5,27536; $P < 0.001$; $r^2 = 7.51\%$; n = 2514 (gardens), 1807 (NW Oahu), 13230 (residential), 1886 (rural), 5630 (urban), 2475 (Waialua).

in protein trap captures in rural south and northeast Oahu but also in winter months of 2010 and 2013 in Waialua (Figs 2b, 4b).

Oriental fruit fly captures in methyl eugenol traps were highest on the windward side (Waialua and Northeast Oahu), intermediate in rural south sites, residential sites and community gardens, and lowest in urban sites (Fig. 5a). Protein traps, on the other hand, collected fewer than 10 per trap per week at most sites (Fig. 6a). Oriental fruit flies were abundant throughout

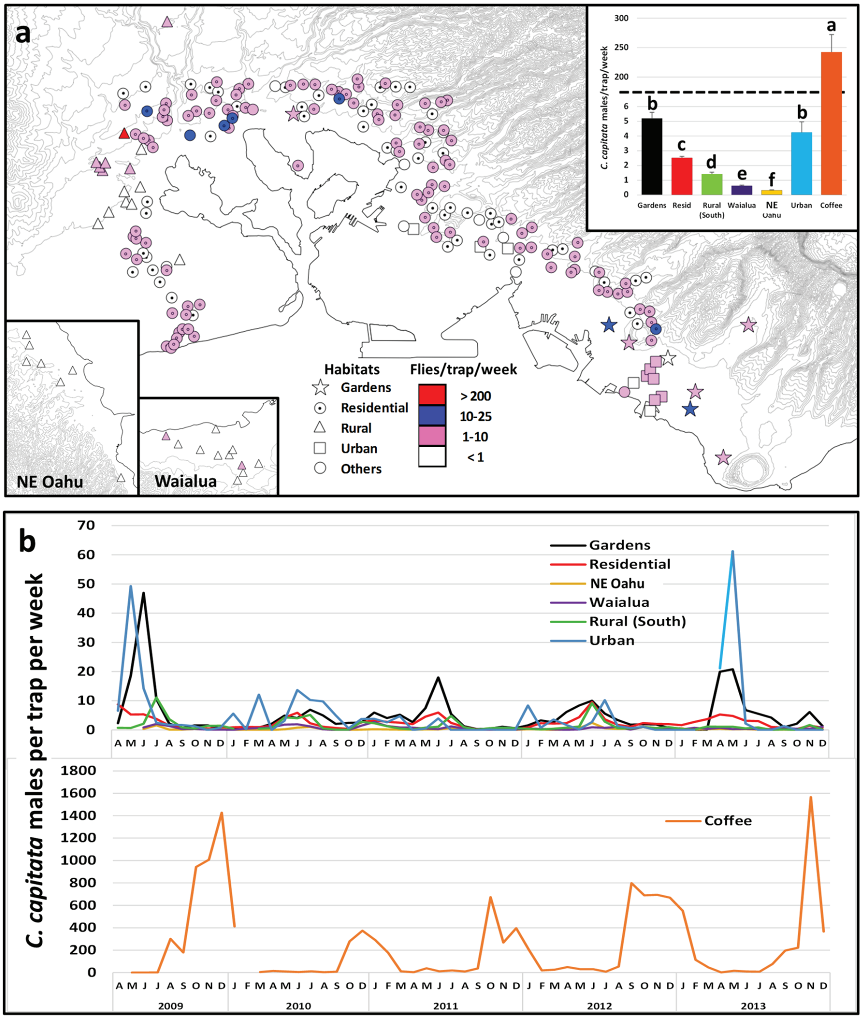

Figure 7a–b. Mean captures of male *C. capitata* per trap per week in trimedlure traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). $F = 586.20$; df = 6,18127; $P < 0.001$; $r^2 = 16.25\%$; n = 228 (coffee), 2514 (gardens), 1807 (NW Oahu), 8879 (residential), 1492 (rural), 739 (urban), 2475 (Waialua).

the year in the rural sites (Fig. 5b), and the seasonal cycles were well defined in most of the regions, with annual summer peaks, generally between May and August, and additional peaks around October of 2012 and 2013 (Figs 2c–d, 5b, 6b).

Mediterranean fruit fly was abundant only at one site, the Hawaii Agriculture Research Center (HARC), on Kunia Road in Waipahu, which contains an experimental coffee plot in proximity to the traps (Figs 7a, 8a), as well as host mock

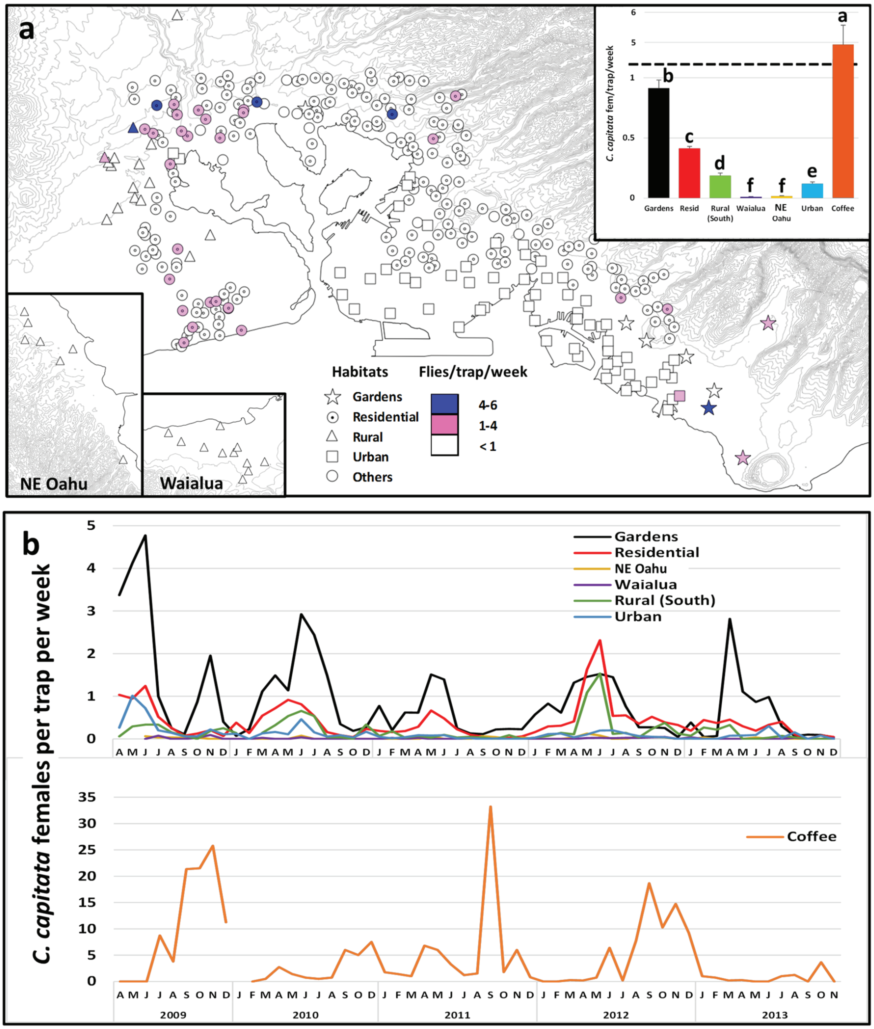

Figure 8a–b. Mean captures of female *C. capitata* per trap per week in torula yeast traps at different sites (a), in different habitats (a, insert graph), and as monthly means throughout the trapping periods in different habitats (b). Values with the same letter in insert graph are not significantly different at the 0.05 level (Tukey's test, post ANOVA). $F = 315.75$; df = 6,27535; $P < 0.001$; $r^2 = 6.44\%$; n = 228 (coffee), 2514 (gardens), 1807 (NW Oahu), 13230 (residential), 1658 (rural), 5630 (urban), 2475 (Waialua).

orange (*Murraya paniculata* (L.) Jack.). It was generally uncommon in other sites, except a few of the community garden, residential, and urban sites. As was the case with the two other species, *C. capitata* trap captures (Fig. 2d–e), other than at the coffee site, were highest during the summer months (June–July) each year and slightly earlier (April-May) in 2013. In contrast, peaks consistently occurred

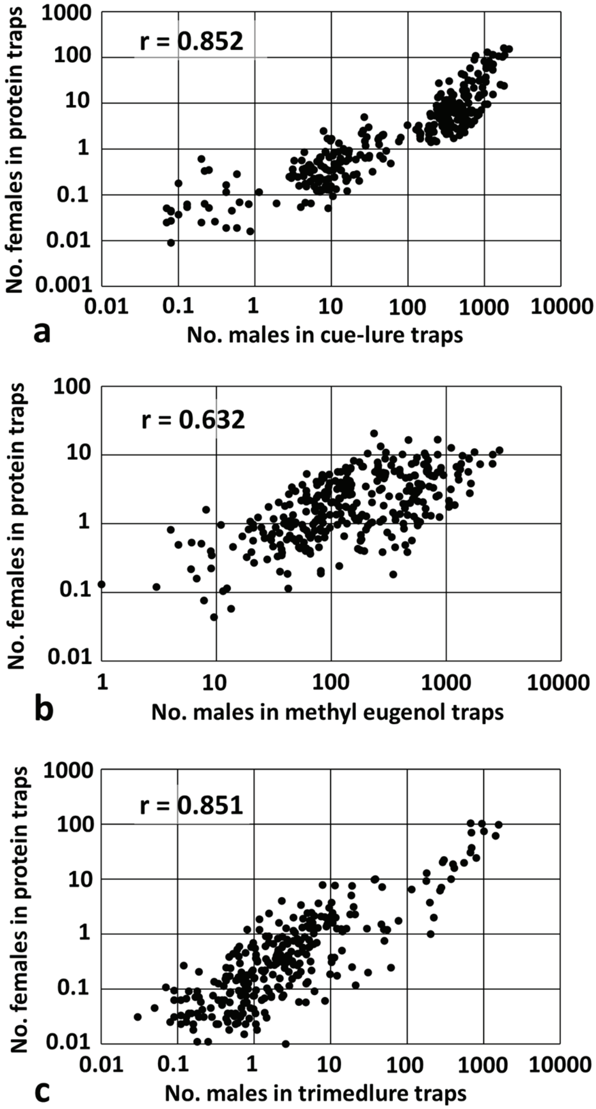

Figure 9a–c. Correlation between mean monthly captures of female flies in protein traps and males in male lure traps for *B. cucurbitae* (a), *B. dorsalis* (b), and *C. capitata* (c).

late in the year (October to December) at the coffee site (Figs 7b, 8b).

Discussion

The summer and sometimes winter population peaks for melon fly in our trap captures were largely consistent with those previously reported in the literature: June to August or November to December on Molokai (Harris and Lee 1989), summer months on Kauai (Harris et al. 1986, Vargas et al. 1989, 1990), or late in the year or during winter in some sites on Kauai (Vargas et al. 1989), and December on Niihau (Vargas 1994). On Kauai melon fly was more abundant and seasonal peaks more pronounced on the drier leeward side, where wild cucurbit weed, rather than garden fruit, provided the main breeding reservoir (Harris et al. 1986, Harris and Lee 1989, Vargas et al. 1989). Consistent with our previous findings (Leblanc et al. 2012), its abundance and seasonal trends on Oahu were heavily influenced by the large-scale commercial cultivation of host crop, with populations highest in the three rural regions, especially the rural south, where cucurbit crops and tomato are grown over extensive areas. The dominant commercial grower in that region, Aloun Farms, grows host material all year, with the main production season for cantaloupe, honeydew melon and watermelon between April and September and a pumpkin crop harvest in September and October (ALOUN 2014), likely responsible for the main summer peaks and smaller peaks observed in the fall, respectively (Fig. 3b).

Higher captures of *B. dorsalis* in methyl eugenol traps on the windward than leeward side are consistent with the pattern observed on Oahu (Leblanc et al. 2012) and Kauai, where population trends were shown to be influenced primarily by guava and strawberry guava, the main hosts sustaining oriental fruit fly populations on that island (Vargas et al. 1989). On the other hand, the summer peaks reported here are in contradiction with the general literature, where flies were generally scarce during March-April and most abundant during September to November, which coincides with the main guava fruiting season, on Oahu (Bess and Haramoto 1958, 1961, Bess et al. 1963, Newell and Haramoto 1968, Haramoto and Bess 1970), Maui (Kula) (Wong et al. 1985b), Hawaii Island (Kona) (Klungness et al. 2009), and Kauai (Stark et al. 1991, Vargas et al. 1983b, 1989, 1990, 2013). Trapping in these previous studies was generally done at or in proximity to forested sites with high concentration of guava, while the present trapping was in residential areas and rural sites, mostly distant from forest. In our previous study, we found that the proximity of forest, with its associated guava, greatly enhanced captures of *B. dorsalis* (Leblanc et al. 2012). The summer peaks observed in our sites, at least in residential areas, were more likely associated with fruiting of planted backyard fruit trees, and especially mango, which main fruiting season (HDOA 1996) matches the summer peaks observed in our graphs. Such summer peaks were also reported in some sites of Maui (Kula) (Wong et al. 1985b), and in Niihau, where oriental fruit fly populations were concentrated around villages, with mango, rather than guava, as its main host (Vargas 1994).

Higher captures of Mediterranean fruit fly in the leeward than windward sites were also reported on Oahu (Harris and Lee 1987, Leblanc et al. 2012) and Kauai (Vargas et al. 1983a). Seasonal peaks in literature were widely variable, depending on local host fruit availability. Summertime peaks, as in the current study, were reported on Maui (Kula) (Wong et al. 1985a) and Niihau (Vargas 1994). The late year peaks at the coffee site were also observed in the Kona coast, where coffee is commonly cultivated in proximity of avocado orchards (Klungness et al. 2009). Seasonal peaks are also known to vary with fly density, with one peak (April to September) in high density areas and two peaks (February to July and September to December) in intermediate density areas in suburban areas of Oahu (Harris and Lee 1987), or peaks in May in high density areas and January to April in lower density areas of Oahu (Vargas and Nishida 1989). Based on five years of trapping in the leeward Makaha and Waianae valleys, annual peaks occurred at different periods of the year, largely influenced by phenology of feral coffee fruiting in the heads of valleys, with flies dispersing to residential areas during the peak seasons (Harris and Lee 1986). Feral coffee breeding and annual dispersal were also documented on Kauai by Vargas et al. (1983a), with peaks in June to November in Waimea valley and August to November in Hanapepe valley.

Mock orange, commonly planted as ornamental edge shrub, is the most heavily infested among the available hosts in residential areas (Nishida et al. 1985, Harris and Lee 1987). Its fruiting season ranges from January to June, though actual fruit availability can be highly variable (Harris et al. 1991). Other hosts commonly infested by *C. capitata* in residential areas, and contributing significant numbers of flies on Oahu, are guava, false kamani (*Terminalia catappa* L.), Surinam cherry (*Eugenia uniflora* L.), mango and citrus (Nishida et al. 1985, Vargas and Nishida 1989). Of these, at least mango peak season (HDOA 1996) matched the main *C. capitata* summer abundance peaks. The late annual peaks at the HARC site (Figs 7b, 8b) were unrelated to those from the other sites and dependent on the availability of ripe coffee berries, rather than backyard fruit.

While feral coffee can be a determining factor influencing *C. capitata* populations and cultivated coffee can locally sustain very large populations (Vargas et al. 1995, Leblanc et al. 2012), these latter large populations remain very localized, with trap captures dropping quickly within a short distance. While trimedlure trap captures were very high (> 200 per week) at the HARC, near the coffee plot, traps in the four sites within 1-km distance, the nearest 400-m distant, collected fewer than 10 flies per week (Fig. 7a).

Very few *B. latifrons* were captured, with most (96 of 111) of the specimens in the rural sites, and 77 of these in Waialua. This species is widespread and commonly infests cultivated solanaceous crops in residential areas and gardens, where 15 specimens were collected in our study. But its primary hosts are wild *Solanum* species (Liquido et al. 1994), such as turkey berry (*S. torvum* Sw.), a common weed around farms, likely explaining the more common occurrence of this species in rural areas.

The seasonal fluctuation cycles in the male lure (Figs 3b, 5b, 7b) and protein (Figs 4b, 6b, 8b) traps were remarkably consistent across the different habitats for all three species. The Pearson correlation coefficients, based on the monthly means by habitat displayed on Figs 3-8 (n=384 pairs of means), were very high: 0.851 for LOG_{10} transformed data and 0.768 for untransformed data for *B. cucurbitae* (Fig. 9a), 0.632 and 0.5 for *B. dorsalis* (Fig. 9b), and 0.852 and 0.888 for *C. capitata* (Fig. 9c). Correlation based on monthly means for individual sites (n=4793) were lower, though still significant ($P < 0.001$): 0.722 (transformed) and 0.429 (untransformed) for *B. cucurbitae*, 0.395 and 0.256 for *B. dorsalis*, and 0.54 and 0.479 for *C. capitata*. Therefore male lure and protein trap captures are both reliable indicators of the fluctuation cycles in seasonal abundance, at least in the sites covered in this study.

Oahu is a densely populated island with extensive residential areas, generally more distant from forest, with high guava density, than on the other Hawaiian Islands. Fruit fly abundance and seasonal cycles in these habitats appear to be dictated by the availability of fruit from planted ornamental trees and shrubs, on which both *B. dorsalis* and *C. capitata* breed (Harris and Lee 1987), rather than the proximity of coffee or guava. Also, peak seasons for these two species appear to coincide with the main mango fruiting season. It would be beneficial in the future to monitor host phenology and sample fruits, while maintaining traps, throughout the year to determine levels of infestation, hence which hosts are primarily responsible for sustaining fly populations and determining their abundance cycles. The information generated through these studies will help in the surveillance and fight against invasive fruit flies in residential areas of California and Florida.

Acknowledgements

This trapping program was initiated with the hard work from Vernon Harrington, Wesley K. Sawamura and Stuart H. Stein (USDA-APHIS). We thank Roger I. Vargas and my hero Ernest J. Harris (USDA-ARS) for discussions on fruit fly ecology and their suggestions for the improvement of the manuscript. In addition to USDA-APHIS funding this program, financial support was provided by Farm Bill funding (project 3.0251), through a Cooperative Agreement between USDA and the University of Hawaii College of Tropical Agriculture and Human Resources (UH-CTAHR), and USDA-NIFA Hatch projects HAW00942-H and HAW00956-H, administered by UH-CTAHR.

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