

Targeted Trapping, Bait-Spray, Sanitation, Sterile-Male, and Parasitoid Releases in an Areawide Integrated Melon Fly (Diptera: Tephritidae) Control Program in Hawaii

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Abstract: An areawide integrated pest management approach to melon fly *Bactrocera cucurbitae* (Diptera: Tephritidae) suppression in Kamuela, Hawaii, was undertaken as part of a larger statewide program by the U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS), Areawide Initiative. After a survey on five islands, a grid of 1 trap/km² over 40 km² was established in Kamuela to locate areas of infestation. Then a targeted male trapping array was applied based on the distribution of host plants, and these were mapped using geographic information systems. Trap density was determined by monitoring existing traps and by increasing density where catch was high. Sanitation of crops, application of GF120 Naturalyte NF bait spray, Sterile Insect Technique (SIT), and augmentation of *Psytalia fletcheri* parasitoids were also used. Pretreatment trapping in the farming area indicated a melon fly population peak of 11.94 ± 9.90 flies/trap/day (f/t/d) on 30 Oct. 2000. By 2003, the average catch of the grid traps over 16 wk was 0.016 ± 0.005 f/t/d per km², a 99.87% reduction. Some resurgence of melon fly population to a 12-wk average of 0.191 ± 0.79 f/t/d per km² occurred when USDA discontinued SIT and parasitoid release and bait spray applications. Resurgence occurred primarily in the off-farm areas where growers had not adopted the three suppression techniques (sanitation, bait spraying, and male annihilation). Restoring USDA bait sprays application and briefly reapplying SIT returned the population to a mean of 0.033 ± 0.004 f/t/d per km² between 20 Jan. and 5 April 2004. Between August 2002 and August 2003, infestation in all fruits observed over 40 km² averaged 14.3 ± 2.9%. In 2002, with all suppression activities implemented, the infestation rate averaged 8.5 ± 4.8% in sampled fruit. That is an 83.2% reduction compared with the 2000–2001 mean infestation of 50.6 ± 4.9%.

Keywords: areawide, sanitation, augmentorium, male annihilation, sterile insect technique, augmentation, SIT, Tephritidae, cucurbit, *Bactrocera cucurbitae*, and *Psytalia fletcheri*.

The goal of this study was to determine how to introduce a melon fly suppression methods to growers in Hawaii that would suppress fruit flies in the agricultural areas without significantly affecting the fragile Hawaiian ecosystem and without major expense to the government. For example, the lack of papaya

cull fruit sanitation in the papaya industry leads to very high fly populations of oriental and melon fly in the Puna District of the Island of Hawaii, where seasonal peaks reached 861 ± 174 and 532 ± 116 flies/trap/day (f/t/d), respectively, in 2000 and 2001 (Liquido 1991a,b, 1993; Klungness 2002). Cucurbit growers in Kula, Island of Maui, routinely culled their melon fly–infested fruit onto their cropping fields or in piles near their fields (Klungness et al. 2005). Cucurbit growers in Ewa, Island of Oahu, practiced short cropping; weekly applications of dibrom were used to protect the fruit through a short period of harvesting. Plants were then killed with herbicide to reduce continued fruit set and fruit fly infestation. Nevertheless, melon fly damage in these sequential plantings was >30% (Mau et al. 2003a,b).

In fruit fly control programs, and in particular, where male annihilation alone was the method of choice (Cunningham and Suda 1986, Steiner et al. 1965), the objective has been to saturate the entire area evenly with the male lure specific to the tephritid species. As a mono-technique, male lure trapping has seldom been implemented because most of the available male lures do not greatly reduce the male population. The exception is methyl eugenol, which is used against oriental fruit fly *Bactrocera dorsalis* (Hendel).

Techniques for suppressing *Bactrocera cucurbitae* (Coquillet) were reviewed by Dhillon et al. (2005). The authors emphasized the need for an integrated approach to melon fly management. Early efforts to control melon fly *B. cucurbitae* in Hawaii revolved around the work of Nishida and Bess (1950), Bess (1953), Nishida (1954, 1958) and Nishida et al. (1957), from which the concept of spraying bait (protein hydrolysate) on border vegetation was developed.

Okinawa Prefecture eradicated the melon fly by using a combination of techniques including aerial broadcasting of blocks treated with cue lure and pesticide at ~8/ha and the release of sterile fruit flies (Koyama et al. 2004). Their success rivals all other programs in the world, but it was accomplished at great expense to the government and with demands on the people and the environment that would not be tolerated in the State of Hawaii.

The island country of Nauru, with the help of the Secretariat of the Pacific (Allwood et al. 2001), also undertook eradication of all fruit fly species on the island including melon fly. As with the afore-

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mentioned programs, this always includes the use of a toxicant with cuelure and/or methyl eugenol. Usually the toxicant was malathion or dibrom, used in the lure traps (usually fiber blocks or coconut husk) and in bait sprays applied directly to vegetation.

Since these eradication efforts, safer techniques have been developed that do not use organophosphate pesticides that have highly unspecific toxicity. Spinosad is being adopted in the United States because it has ~0 mammalian toxicity, and has passed stringent tests of its impact on beneficial insects and aquatic organisms (Dow Agroscience, Indianapolis). It is also highly effective against starved *B. cucurbitae* (Prokopy et al. 2003, 2004).

A pilot program was undertaken under the auspices of the Areawide Program of the Agricultural Research Service, USDA, to demonstrate that a combination of existing fruit fly suppression techniques could be applied economically, in cooperation with the growers and members of the community, to suppress (as opposed to eradicate) fruit fly populations in areas of agricultural importance. The objective was to develop a coordinated approach that would respond to the existing density, seasonality, and persistence of the established melon fly populations. The specific objective of this paper is to evaluate the effect of targeted lure trapping in combination with other suppression techniques to suppress melon fly in an integrated pest management system in Kamuela, Hawaii. The null hypotheses are that it is not possible to suppress fruit fly population in a target area surrounded by infested areas, or to transition the use of the techniques to the growers in the target area.

Materials and Methods

Target Species and Demonstration Sites. The project began with an effort to determine the important areas where fruit flies affect the most agriculture, and in which areas the growers would be cooperative and supportive of the program. To that end, we initiated a survey in 1999 on five islands of Hawaii. After initial visits to areas with fruit fly host crops throughout the islands and discussions with the University and State of Hawaii agricultural staff, we selected target areas for a trapping survey. These included five sites spread across five islands: i.e. Kamuela (Kamuēla) in South Kohala District, Puna District and Ka'u District on the island of Hawaii, Kula on the island of Maui, central Molokai, Haleiwa, Kunia and Ewa on the island of Oahu. Data was also considered from the fruit fly eradication demonstration project previously conducted on the island of Kauai (Vargas et al. 2000).

Baseline Trapping (BL). A survey was conducted to determine the baseline population of all four introduced tephritid fruit fly species: *B. dorsalis*, *B. cucurbitae*, *B. latifrons* (Hendel), and *Ceratitis capitata* (Wiedemann). The same trap set that was applied on all the islands was also applied to nine sites in Lalamilo Farm Lots in Kamuela. A site usually consisted of an area in which five traps (with five attractants) could be deployed in different plants within 3 to 6 m of each other. Occasionally the traps were deployed <50 m from first to last trap. The five traps included a male lure trap for each species and a protein bait trap to which males and females of all four species might respond. These traps were monitored on a biweekly basis for 6 mo to 1 yr, depending on how long the sites remained under consideration to be selected as target areas.

The male lure used for melon fly was cuelure (CL, 4-[p-Acetoxyphenyl]-2-butanone, Scentry Biologicals, Billings, MT), deployed in 1- and 5-L plastic buckets (Highland Plastics, Mira Loma, CA) modified with four 1.9-cm entrance holes and 0.3-cm drain holes. The toxicant used in the cuelure traps was 2,2-Dichlorovinyl dimethyl phosphate (DDVP) (Vaportape II, Hercon Environmental, Emigsville, PA). Each baseline trap site (BL) contained one melon fly trap. The bait trap at each baseline site consisted of a yellow-bottom dome trap (Better World Manufacturers, Fresno, CA) baited with either Mesoferm (Corn Products International, Westchester,

IL) or NuLure (Miller Chemical & Fertilizer Corp., Hanover, PA). Additionally, bucket traps baited for *C. Capitata* (trimedlure), *B. dorsalis* (methyl eugenol), and *B. latifrons* (alpha-ionol and cade oil) were deployed at each site. This paper reports only the results for melon fly at the Kamuela target site.

Target Area Selection. Based on the results of the BL trapping data and the active support of the growers and the agricultural staff in each area, three target sites were initially selected for full program implementation because they gave the most promise of successful suppression. The town of Kamuela was chosen as the target area on Hawaii, Kula on Maui, and Kunia/Ewa on Oahu. This study reports only the results for the Kamuela site where targeted trapping was implemented.

Target Species Selection. Melon fly was the primary target for suppression in Kamuela because most of the fruit fly-susceptible commercial crops were hosts of this species. We recognized early in the program that although there were hosts of melon fly in various areas of the grid, they were not ubiquitous. Rather, they existed in cultivated or wild patches (e.g., pumpkin, *Cucurbita moschata* Duchesne ex Lam.) and isolated crops (e.g., cantaloupe, *Cucumis melo* L.; zucchini, *Cucurbita pepo* L. var. *melo*pepo; watermelon, *Citrullus lanatus* (Thumb.) Mansf.; crooked neck squash, *Cucurbita maxima* Duch. ex Lam.; and bitter melon, *Momordica charantia* L.). One of the potential hosts, chayote, *Sechium edule* (Jacq.) Swartz, was widespread in the windward area of Kamuela, but attempts to rear flies from the 478 fruit (71 kg) and vines (2.8 kg) produced only one unemerged puparium. Other wild hosts included bitter melon, *M. charantia* var. *muricata* (Willd.), tohgan, *Benincasa hispida* (Thunb.) Cogn., and miscellaneous squashes, *Cucurbita maxima* Duch. ex Lam., mostly the result of wild cross-pollination. This led us to realize that trapping targeted toward host plant material where melon flies were reproducing would probably be more effective than a uniformly distributed trap grid.

Area Grid Trapping (GT). The intensive control program began in Kamuela with the establishment of a 40 km² grid, including the Lalamilo Farm Lots and a range of land-use categories. Initially the grid was plotted on a map and male lure traps for the four fruit fly species were deployed near or in host plants at 1 per km² between 8 Nov. 2000 and 14 Dec. 2000 (Fig. 1). Based on the availability of host plant material, we obtained permission from individual property owners to deploy traps for each species of fly. *B. latifrons* host plants were scarce, so Lailure traps were only deployed at ~4 sites. These "grid traps" (GT) became the standard of comparison over time for subsequent trap deployment and evaluation.

Geographic Information System: Soon after deploying the initial grid traps, we adopted a geographic information systems (GIS) approach to the trapping program. This included establishing Geographic Positioning System (GPS) coordinates for each grid trap, and for host plants throughout the grid area. Garmin GPS 12 units (Garmin International, Olathe, KS) were used to record GPS coordinates, and later the coordinates were transferred to ArcInfo (Environmental Systems Research Institute, Redlands, CA) mapping software. Data were keypunched directly into ArcInfo datafiles or transcribed to Excel (Microsoft Corp., Kent, WA) spreadsheets and imported to ArcInfo for mapping. Graphical presentations were done with Sigma Plot (SPSS, Chicago) as well as with Excel. Statistical analyses of the data, using procedures CORR, FREQ, GAM (generalized additive models, Hastie and Tibshirani, 1986), GLM, REG, SUMMARY, and STEPWISE were done with SAS (SAS Institute, Cary, NC).

Plant Host Mapping and Fruit Sampling. The host mapping served three purposes: collecting fruit for rearing out fruit flies; documenting the fruiting phenology throughout the grid; and locating and mapping all potential host plant material. Fruit sampling was conducted opportunistically and sequentially; i.e., the available staff would

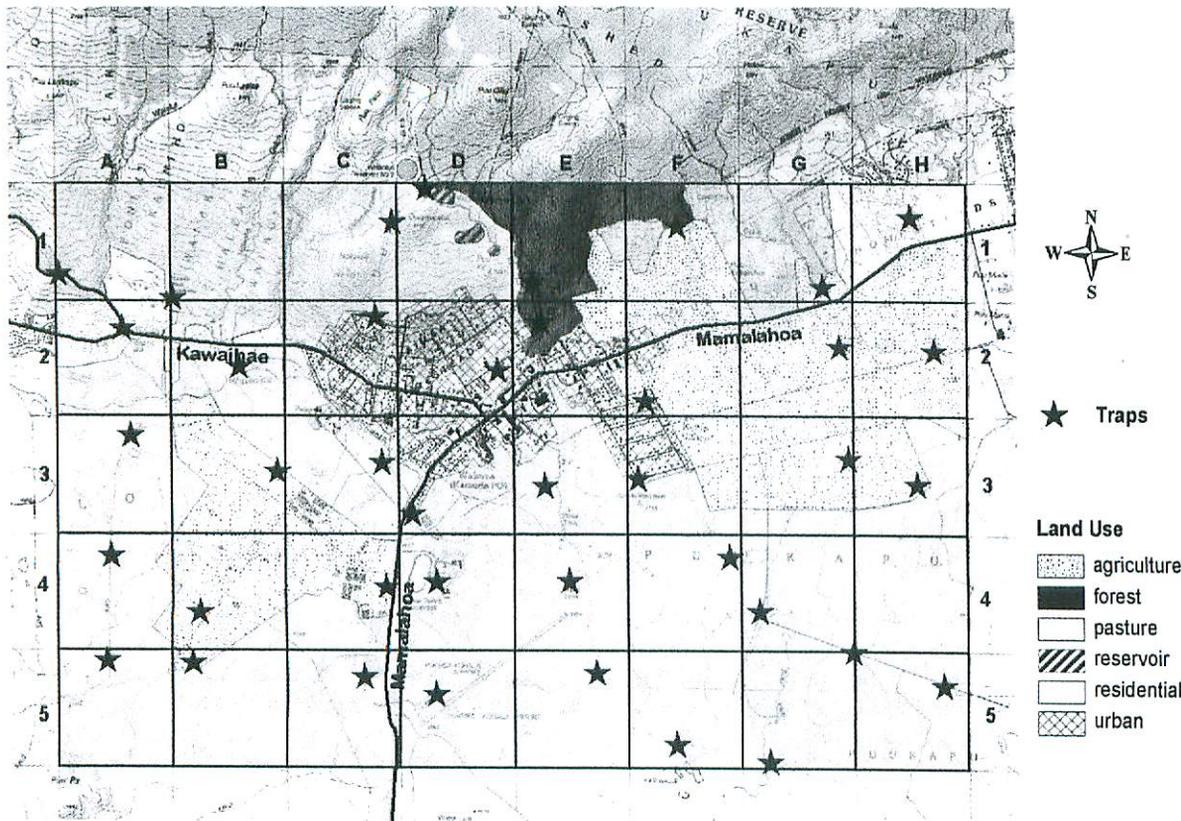


Fig. 1. A map showing the land use zoning of Kamuela and the locations of the grid traps (GT). These are used as the standard of comparison of the population over the duration of the program.

collect as much infested fruit as they could process from as many active sites as they could find at any given time of the year. There was no attempt to make a strictly randomized fruit sampling for two reasons: growers and homeowners objected to a random sampling system that included harvesting healthy fruit, and inadequate labor was available to do random sampling of such a diversified variety of fruit. Therefore, selective samples were only taken of fruit that appeared to be infested. The argument for this limited sampling scheme is that if the sample is restricted to the “damaged” subset, the variance is reduced and a smaller sample size is required.

In addition, for one year (28 Aug. 2002 to 27 Aug. 2003) in the middle of the suppression program, each fruit sampler recorded how many fruits were observed before damaged fruit was found, harvested, and taken to the lab to rear out larvae. This process, often called presence-absence sampling, was repeated once or more at each site. In the absence of damaged fruit at a site, the number of observed fruits was recorded and entered as 0% damaged. Fruits collected per date varied from >10 to <1,000 fruit collected over gardens, orchards, and commercial crops.

This presence-absence sampling method gave us a measure of the percentage of all fruit that were damaged, as well as the percentage of visibly damaged fruit that actually contained larvae (percentage of fruits observed that were infested). In their search for fruit, the crew discovered new host plant loci, and these in turn yielded new sources of fruit. Thus the database grew to allow host mapping and calculation of crop area.

Block Monitoring (BM). The next stage of fly trap deployments was neither “blocking” (deploying saturation numbers of male annihilation traps on a uniform distribution pattern for the sole purpose of killing male flies) nor “monitoring” (deploying a limited number of traps on a uniform distribution to monitor the population). Instead, we pursued a focused approach for logistic reasons (limited staff) and legal reasons (state law at that time required that all traps be monitored). The available trap catch data from the grid and baseline traps were used to identify potential hot spots (areas of

high trap catch). Knowledge of host plant distribution and phenology was incorporated in deciding where to deploy additional traps. These traps were intended to accomplish mass male annihilation, while being monitored to obtain data to localize areas of melon fly breeding. The number of traps deployed in an area varied as a function of host plant density and number of flies captured.

In the sixth year of the program, the only registered use of cuelure traps was for monitoring purposes. Under U.S. the Environmental Protection Agency regulation Å§24(c) of FIFRA, emergency registration was obtained from the State of Hawaii Dept. of Agriculture to deploy traps containing Dibrom Concentrate and Cuelure. Although 98 inverted-bucket traps containing this mixture were deployed, safety regulations made the use of liquid toxicant impractical, and it was abandoned. Instead, the DDVP toxicant strip was used in BM traps, until later in the program when these bucket traps were replaced with one-way traps that did not require a toxicant (Tan 1985, Hiramoto et al. 2006, EBJ, unpublished) and needed to be serviced less frequently.

Protein Bait Traps (PB). Protein bait traps deployed in areas with host plants provide an early indicator of emerging flies because the flies begin to search for food soon after eclosion. Therefore, the staff deployed protein bait traps at a density ≥ 2 per active crop site (including wild or garden patches of pumpkin). A new bait product, Solulus (Roquette America, Keokuk, IA) buffered with 5% borax (U.S. Borax, Scottsdale, AZ), was found to attract melon fly better than other baits currently in use by the USDA (GTM, unpublished data).

Deployment of Suppression Technologies. Five suppression technologies were used in this program: (1) Cuelure traps were deployed for male annihilation as described in the section on BM. (2) Sanitation was implemented through the use of augmentoria (Klungness et al. 2005, Jang et al. 2007) and/or the growers’ disposal of the culled fruit by bagging it and hauling it to a municipal garbage collection site. (3) Bait spraying was accomplished with GF120 Naturalyte Fruit Fly Bait (Dow AgroScience, Indianapolis), and later with Dow’s organic formulation (GF120 NF Naturalyte Fruit Fly Bait)

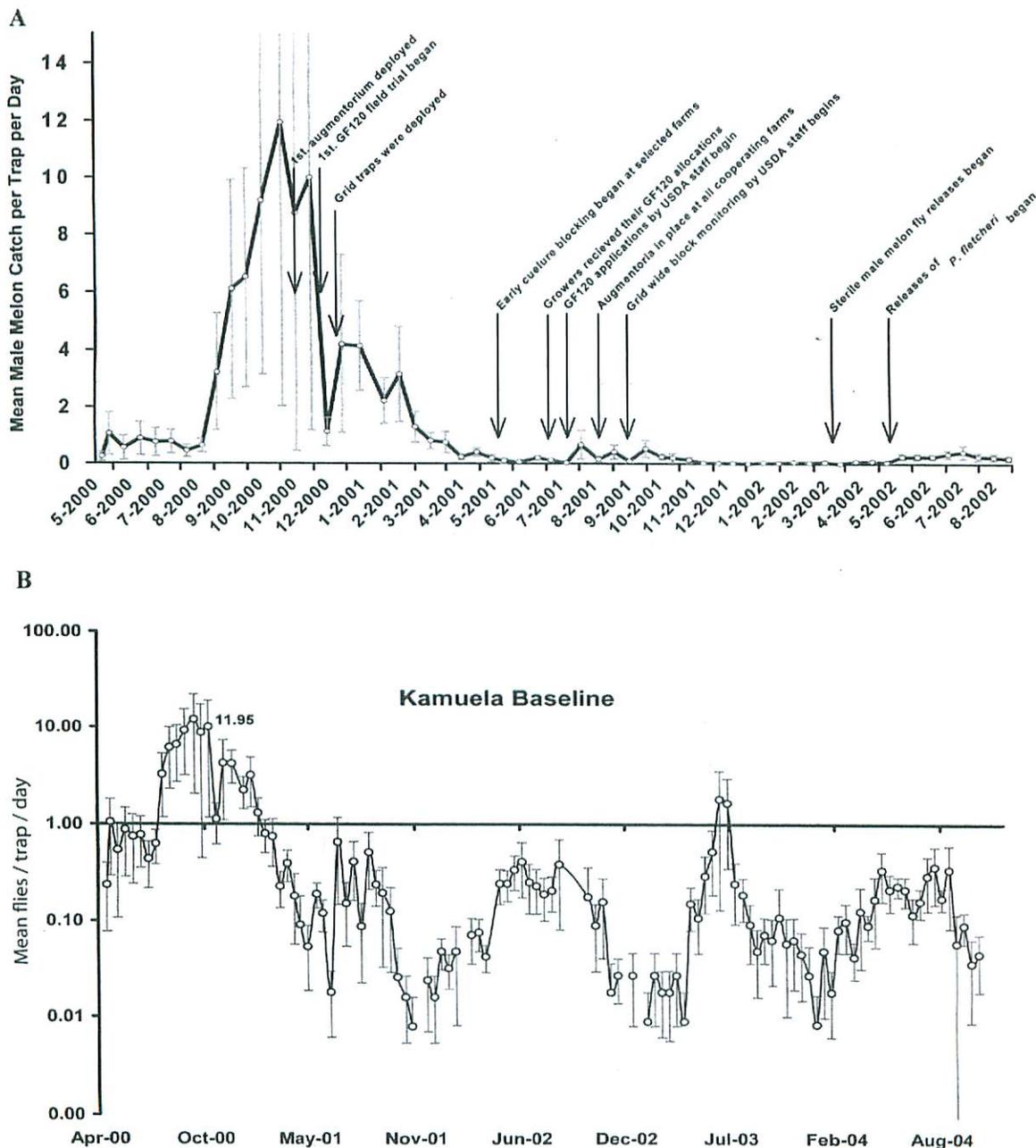


Fig. 2(a). Baseline biweekly means are shown for the cuelure traps at 9 locations in Lalamilo Farm Lots. Timing of the suppression treatments is indicated by arrows. **(b).** Baseline biweekly means are shown for the duration of baseline sampling in Lalamilo farm lots.

certified by the Organic Materials Review Institute (Eugene, OR). (4) Sterile male melon flies (SIT) were released using flies produced by the USDA Fruit Fly Research Laboratory, Manoa, HI (McInnis et al. 2004). (5) Parasitoid augmentation was also implemented using *Psytalia fletcheri* (Silvestri) produced at the USDA Manoa lab (Bautista et al. 2000). The application of GF120 and the distribution of SIT flies and parasitoids were all determined by examination of the male lure and protein bait trap catch on a weekly basis. With the exception of sanitation (discussed in the next section), areas of highest fly recovery received the concentrated application of these suppression technologies. Thus labor resources were concentrated on areas of greatest need.

Time Schedule. The rate at which the program was implemented was a function of available labor and the availability of technologies, such as the sterile male melon fly strain developed by McInnis (2004). Each of the suppression techniques was brought into play in stages. Fig. 2a illustrates the timing of that implementation.

Sanitation. Augmentoria deployments are described in Jang et al. 2007.

BM Traps. Table 1 tracks the deployment of traps as parameters

of the program's progress. At peak deployment, 378 cuelure traps (332 BM, 38 GT and 8 BL) were being monitored. A melon fly dispersal study (Peck et al. 2005) was added to Lalamilo Farm lots in October 2002, and those 48 traps were maintained until September 2003. Subsequently, as various suppression techniques were added, the number of cuelure traps monitored (BM) was reduced.

Bait Spray. In June 2001, the bait spray was distributed to the growers and its application was demonstrated. GF120 applications by the USDA staff began on 27 July 2001, applying 4.46 L to melon fly host and border vegetation around the grid. These applications continued, with interruptions, until 15 Dec. 2005

Parasitoid Augmentation. Release of *P. fletcheri* began at an east grid site on 10 and 17 April 2001, again on 7 and 14 Nov., and on 5 Dec. 2001. Beginning 10 April 2002, wasps were released at between two and eight sites about every week until 20 March 2003. These releases were made from screen cages which were held under control environment during eclosion, after puparia were shipped from Honolulu. These cages were hung in locations near melon fly crops; and the quantity of wasps released varied because of fluctuations in the preshipment estimated eclosion (total: ~766,988 ♀♀)

Table 1. Deployment of block monitoring (BM) and other cue lure traps in Kamuela.

Date of change	No. grid traps (cue lure)	No. BM traps	No. blocking traps	Peck test traps	Dibrom + cue lure blocking traps	Total cue lure traps deployed
21 Dec. 2000	40	0				40
3 April 2001	37	200				237
29 Aug.	37	311				348
2 Jan. 2002	37	300	11			348
5 March	37	270	41			348
30 May	37	180	131		139	487
1 Oct.	37	100	211	48	139	535
7 April 2003	37	102	192	48		379
2 June	37	20	291	48		396
3 Sept.	37	25	286	48		396
22 Sept	37	26	239	48		350
24 Feb. 2004	37	23	239			299
1 July	37	49	239			325

and estimated survival (total: ~173,779 ♀♀) after shipping and holding for release. The mean number of female wasps released per date was $3,457 \pm 504$.

SIT (Sterile Insect Technique). The releases of color-strain sorted sterile male melon flies were initially restricted to $4 \times 5 = 20 \text{ km}^2$ in the northeast quadrant of the grid area. This area was the site of rapid increase in melon fly population as well as an area where little suppression activity was being conducted by the residents. USDA staff were trapping and applying GF120 in some localized areas of this quarter of the grid. After one SIT release on 8 Nov. 2001, roughly weekly releases began 20 Feb. 2002 by releasing flies from stationary buckets at preselected sites. Releases continued in the east grid until 2 Oct. 2002. Within this time, the SIT fly releases expanded to areas of higher fly population throughout the 40 km^2 grid. Releases transitioned from stationary bucket releases to a mobile release of flies from a moving vehicle along a pre-selected course. The releases were suspended because of production problems, and SIT flies were not available for use in Kamuela until the following fall. They were released between 13 Aug. 2003 and 13 Nov. 2003 in the Hawaiian Homelands areas of the east grid, where melon fly populations had rebounded.

Project Reorganization

Roger Vargas took over management of the project from Eric Jang on 4 December 2001. In 2002, emphasis began to shift from melon fly suppression to the control of oriental fruit fly in the Kamuela grid and the deployment of baseline traps of North Kohala District. Consequently, labor constraints forced a rollback of melon fly suppression activity in Kamuela. Not only were SIT and parasitoid releases stopped on 18 Dec. 2002 and 6 Nov. 2002, respectively, but the GF 120 applications were discontinued on 23 May 2003 and not resumed until 12 July 2003. The BM was reduced to only the actively producing commercial crops, and PB monitoring was reduced to two traps per crop on commercial farms. Three hundred and twenty-nine cue lure blocking traps remained throughout the grid and were recharged on a tri-monthly basis.

During this transition, a post-doctoral scientist changed all fruit sampling procedures to a strictly randomized method, which meant that many samples contained no fruit. This survey technique resulted in too few cucurbit host fruit samples to assess melon fly infestation.

During this rollback in government staff activity, growers were encouraged to take precautions such as monitoring their own traps, applying GF120 more regularly, and be particularly cautious about sanitation. BM traps were recharged and remained a constant suppression factor throughout, although few were monitored after the change in strategy. GF120 was applied throughout the grid over the course of the project, with the exception of three interruptions of 50, 56, and 170 d on 2 May 2003, 11 March 2004, and 17 Nov. 2004, respectively. SIT and parasitoid releases were altered according to availability of insects.

Once it was apparent that the cutback in suppression activity had led to a resurgence of melon fly population in some areas, a sporadic return to GF120 application began on 18 July 2003 and SIT was resumed at two sites on 13 Aug. 2003. Parasitoid releases were not resumed. The USDA-ARS suppression activity continued longer, but for the purposes of this comparison, this study includes grid trapping data to 1 Nov. 2005, but fruit eclosion data only extends to 8 April 2003.

Technology Transfer. The objective of the Areawide Program was to transfer the technology to the growers. Therefore, throughout the suppression period, commercial growers were encouraged to participate in the control measures by applying GF120 bait sprays, practicing sanitation of cull fruit, tilling quickly after harvest, and deploying their own male annihilation traps. To that end, weekly updates of fly populations in their fields were provided to the growers. A supply of GF120 (max. 298.4 L), augmentoria in each farm, and advice about areas where fly numbers were rebounding were also provided.

In areas where the growers were not applying the techniques themselves, the USDA crew supplemented all of the above techniques except sanitation. Only a small portion of the grid area contained active farming land, but the remaining residential and rural land contained melon fly host plants. Similarly, SIT and parasitoid augmentation were provided by the USDA.

Results

Baseline Trapping (BL)

Fig. 2b reports the results of the BL trapping in Kamuela from inception to 1 Nov 2004. The melon fly population mean reached 11.95 ± 9.91 flies per trap per day (f/t/d) in the fall of 2000, primarily because of the infestation in the cucurbit crops in Lalamilo Farm

lots (west side of Kamuela). Initial localized efforts to control the flies began with a field trial in those fields, but full implementation of the suppression program was not complete until the following fall. Melon fly population exceeded 1 f/t/d only once after 1 Feb 2001. The average trap catch in Lalamilo Farm Lots after that date was 0.25 ± 0.03 f/t/d.

Grid Trapping (GT) Measuring Combined Impact Of Techniques

The grid trap data were used as a standard of comparison throughout the suppression period. It was apparent in the first year that the three techniques (sanitation, male annihilation, and GF120) were able to reduce the melon fly population, as indicated by data from the grid traps deployed at 1 trap per km² (Fig. 3a). The average trap catch between May and December 2001 was 0.215 ± 0.068 f/t/d per km² (a 13.9-fold reduction from the mean f/t/d on 12 Dec. 2000). With the addition of SIT and *Psytalia fletcheri* in 2002, the population was driven even lower, averaging 0.016 ± 0.005 f/t/d (an additional 13.4-fold reduction from 2001, and 804.3 times lower than the peak population in October 2000).

When the government crew suspended application of GF120 in May 2003, parasitoid releases in September 2003, and SIT release in December 2003, a resurgence of melon fly population began, particularly in areas that were not commercial farms, or where the growers were not applying GF120. This tended to be in the eastern part of the 40 km² grid (Fig. 3a). A fourth-degree polynomial model of male melon fly catch over time ($y = -2.0 \times 10^{-9} X^3 + 0.0002 X^2 - 6.7011 X + 84671$; $R^2 = 0.4368$; $F_{4,118} = 22.88$; $Pr > F = 0.0001$) describes a negative population trend that is associated with 44% of the total variation in mean fly captures per km² (Fig. 3b). Whereas the grid mean started as high as 4.26 ± 3.27 f/t/d, the mean grid trap catch from November 2001 to November 2005 was 0.10 ± 0.02 f/t/d (Fig. 3b), indicating a 42.6-fold decrease in melon fly in Kamuela.

Block Monitoring (BM) and Targeted Trapping

Throughout the period of block monitoring, localized resurgent populations were detected by the targeted BM distribution of traps (Fig. 4), which were highly clustered around the host material. Therefore, the average of these more strategically located traps was higher than the grid, and more closely reflected the localized population fluctuations (Fig. 5). Between September 2001 and January 2003, there was a negative trend in fly captures. This covered the period during which all suppression activities were implemented.

Two of the lowest BM average numbers of f/t/d (Fig. 5) occurred in the eastern grids in March and May 2003. Thereafter, the eastern grid population climbed steadily until it was approaching the highest recorded mean catch in the baseline monitoring period in 2000. BM

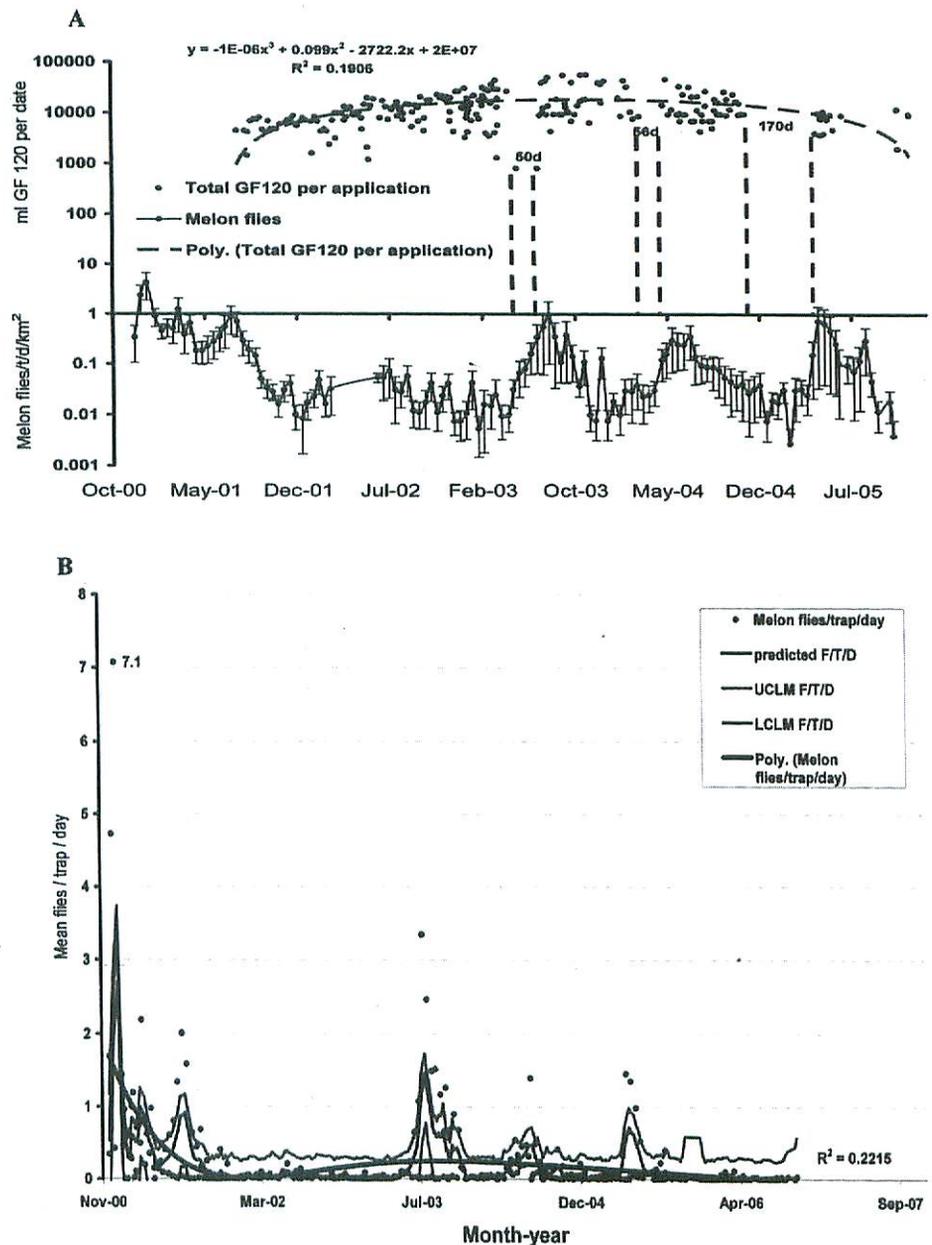


Fig. 3a. Grid trap average melon fly/trap/day/Km². The application of GF120 Naturalyte bait spray is overlaid and the 3 periods of ≥ 50 d suspension of GF120 application are shown. The period of SIT releases is also shown. **(b).** Trendline model and GAM smoothing curve (with 95% conf. limits) of grid trap average melon fly/trap/day/Km².

traps on melon fly crops in the west grid began to indicate a population increase, but the rate of increase was much less (≤ 1 f/t/d).

Sterile Insect Technique (SIT)

The only technique that was purposely not distributed throughout the grid was the SIT releases, as indicated by the ratio of sterile to wild male melon fly captures (Fig. 6). Therefore, we can show that cuelure trap captures remained < 0.1 f/t/d in the 20 km² release area throughout the spring and summer of 2002. It is important to note that the non-release area contained the concentration of commercial farms growing melon fly susceptible crops. After the SIT fly releases were distributed grid wide, the whole grid was reduced to < 0.01 f/t/d by the rigorous standard of the on-crop block monitoring (Fig. 7). Cropping of those susceptible crops continued into the fall and winter, so the reduction from a maximum 0.6 to a minimum 0.007 f/t/d indicated a probable SIT impact up to 21 Jan. 2003 (Fig. 5). A

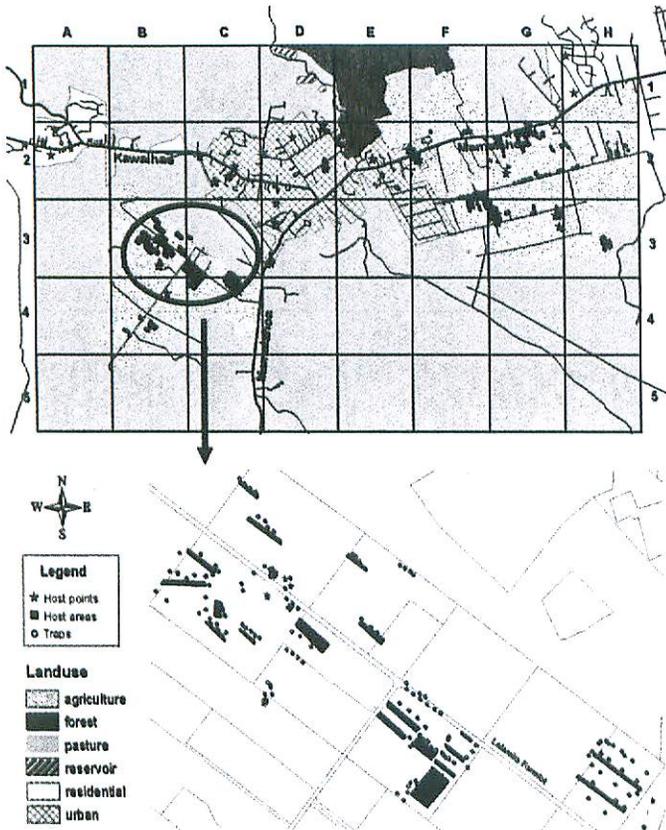


Fig. 4. A map showing the deployment of all melon fly block monitoring traps (BM) in the Kamuela grid in relationship to the location of the melon fly host patches and fields. The Lalamilo Farm lot area is enlarged below the grid map to show the relationship of fields to traps. Crops in these areas were rotated, so not all the host locations are shown, but this represents an average distribution of the host material at one point in time.

total of ~6,122,000 sterile flies were released; and of those, 3.4% (208,312) were trapped by the winter of 2003. The significant effect of the SIT on egg mortality is reported in McInnis et al. 2007

The reintroduction of SIT in August 2003 was concentrated in the east grid, where the population had rebounded at a few sites to near presuppression levels. Approximately equal numbers of sterile males were released at two farms totaling ~455,040 flies. This was

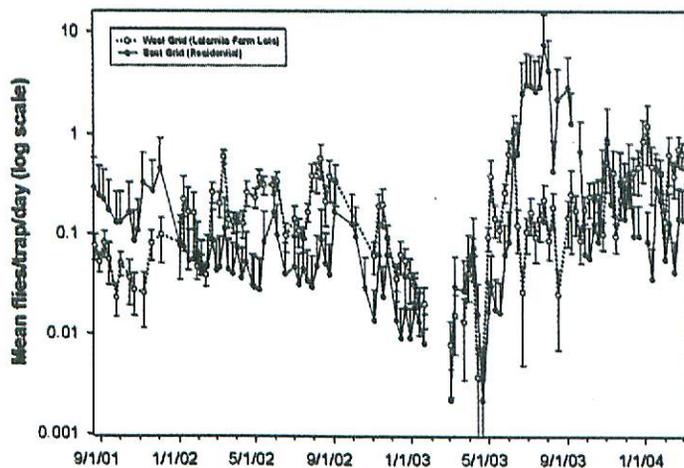


Fig. 5. The weekly mean block monitoring trap captures from 22 Aug. 2001 to 8 March 2004. The west grid data (Lalamilo Farm Lots included) are plotted separately from the east grid which, although zoned as agriculture land, is primarily residential neighborhoods and Hawaiian Homelands.

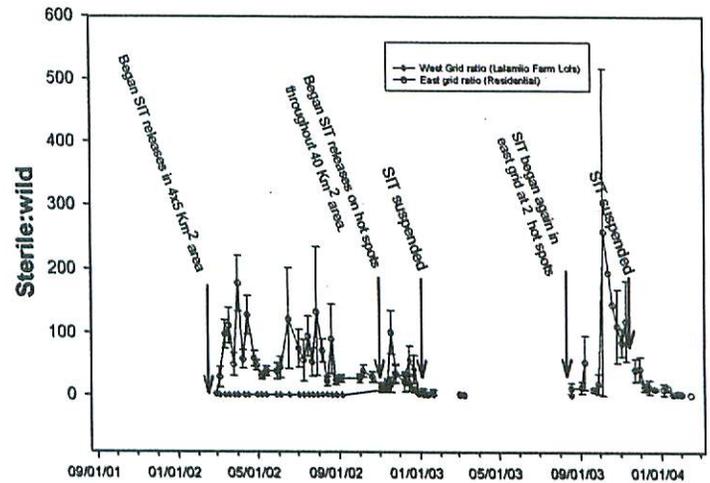


Fig. 6. Ratio of recapture of sterile male melon flies to wild flies in the east and west areas of the grid. Timing of releases is indicated.

necessary to contain the outbreak occurring in the east grid during that time period (Fig 7). This outbreak followed within 2 mo of the end of intense suppression activity by the government staff throughout the Kamuela grid.

The west grid, containing the Lalamilo farm lots, did not experience the great increase in melon fly population even though commercial fields of melon fly host crops were in production there. The growers in Lalamilo Farm lots were conscientious in their sanitation and bait spraying practices.

This was not the case in the east grid. In particular, two organic growers abandoned their cucurbit crops which probably played a significant role in the population increase on the Hawaiian Homelands subdivision. There were also patches of wild pumpkin and tohgan on the properties of these two growers and other properties in the area. Few of the property owners in this area assumed responsibility for controlling their own fly population, as reflected in the higher populations of flies.

Parasitoid Augmentation

The effect of parasitoid wasp releases was the hardest to measure. Emergence of *P. fletcheri* from infested fruit is our only long-term measure of the parasitoid activity. Over the period of fruit sampling, in spite of the decline in number of larvae per gram of damaged fruit, we detected a positive correlation in numbers of *P. fletcheri* recovered

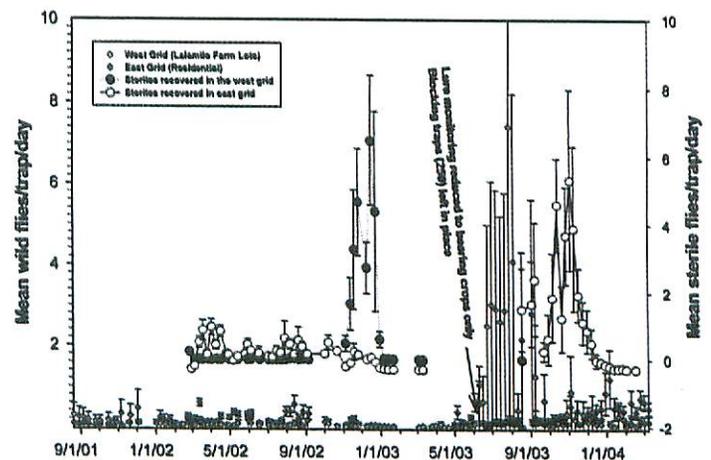


Fig. 7. The recapture of sterile flies is overlaid on the capture of wild flies from the east and west grids, with the specific purpose of showing the relationship between the SIT activity and the wild population, as well as the surge in the east grid in 2003 when SIT and bait spraying were suspended.

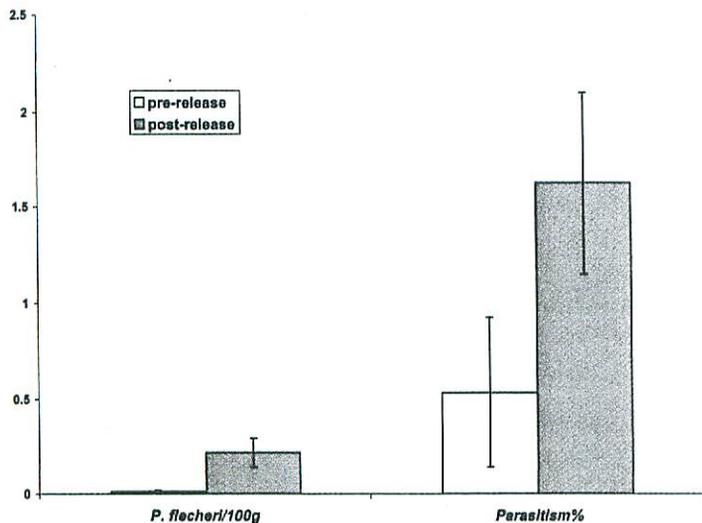


Fig. 8. The effect of *Psytalia fletcheri* releases on the mean number of wasp progeny recovered from all sampled fruit is presented as percentage of parasitism and per gram of fruit.

per gram of all species of damaged melon fly host fruit over time (Spearman's $R^2 = 0.1102$; Prob < |R| = 0.0088; $n = 546$). However, it should be noted that when we ran the correlations on individual host crops, all were positive but none was individually significant. Yet these rates of parasitism were low. Over the entire period, cucumber averaged the highest parasitism, 0.0115 ± 0.0185 *fletcheri*/g of damaged fruit. This represents $8.157 \pm 3.373\%$ parasitism. The lowest rate of parasitism was found in cantaloupe (0.0003 ± 0.0003 *fletcheri*/g or $0.765 \pm 0.765\%$ parasitism). Over all the fruit data, the mean parasitism by *P. fletcheri* was 0.13 ± 0.05 *fletcheri*/100 g of damaged fruit, or $1.14363 \pm 0.31817\%$ parasitism (live adult wasps/total fly larvae). Some researchers would calculate the parasitism as live adult wasps/live adult fruit flies (Eitam and Vargas, 2007), which yield a much higher percentage of parasitism in that it eliminates larval mortality from the proportion. Our calculation represents wasps surviving out of all the host insects. Fig. 8 breaks this down to pre- and post-release means. Although there was a significant increase in parasitism, it averaged <2% (live adult wasps/total fly larvae).

Sanitation

The only measure that we have of the effect of the other techniques on adult fly population is the numbers of flies trapped. Flies enclosed and captured in augmentoria were our only measure of the effect of sanitation. Grower use of the augmentoria was limited. In most cases, the growers preferred to remove the infested fruit from the field and dispose of it at the municipal refuse center or to feed livestock. It should also be noted that all flies do not emerge in the enclosed environment of the augmentorium, particularly when it is full of fruit. Moisture is an important influence on pupation and survival (Jackson et al. 1998), but larvae do not survive well in rotting fruit. Nevertheless, 21,214 flies were recovered from all augmentoria by 4 May 2004. In comparison, 28,864 wild flies were trapped in as many as 137 BM and GT cue lure traps as of 5 April 2004. Therefore, the contribution of 15 augmentoria to reducing fruit fly population was substantial when compared with trapping (Klungness et al. 2005, Jang et al. 2007). The potential first-generation progeny (Vargas et al. 1984) of the ~10,600 females that emerged in these augmentoria is estimated to be >3.3 million.

Sampling of Fruit Infestation

Although the melon fly has not been eliminated from the target zone, the percentage of infested fruit has diminished from > 50% to < 20%. The initial sampling method (when only damaged fruit

were reared out), was abandoned in 8 April 2003. Up to that date, the infested fruit sampling scheme throughout Kamuela indicated a decline of melon flies emerging per gram of fruit sampled, although the model is only associated with 7.2% of the total variation (Fig. 9a). These fruit were only the visibly damaged fruit, not a random sample of all fruit. The highest infestation (>0.4 larvae per g of fruit, Fig. 9b) occurred before the spring of 2001, and the steepest decline in larvae/g occurred in the first year. After November 2001, the larvae/g/date remained <0.10 g on 72.5% of the dates.

Applying nonparametric Spearman's regression to the mean number of melon flies per gram of all damaged host fruit per sampling date did not yield a significant trend over time ($R = 0.01065$; Prob. of $R = 0.8190$). However, when the analysis is broken down by host plant species (Table 2), it became immediately apparent that the trend differed between commercial hosts (on farms) and noncommercial hosts (in small gardens or wild patches). Among the latter, the trends were negative and correlated to between 0.4 to 47% of the variation, whereas, in the commercial crops, the trends (0.004 to 0.586% of the variation) were mostly not significant. The exception was zucchini in which 3.8% of the variation was positively correlated over

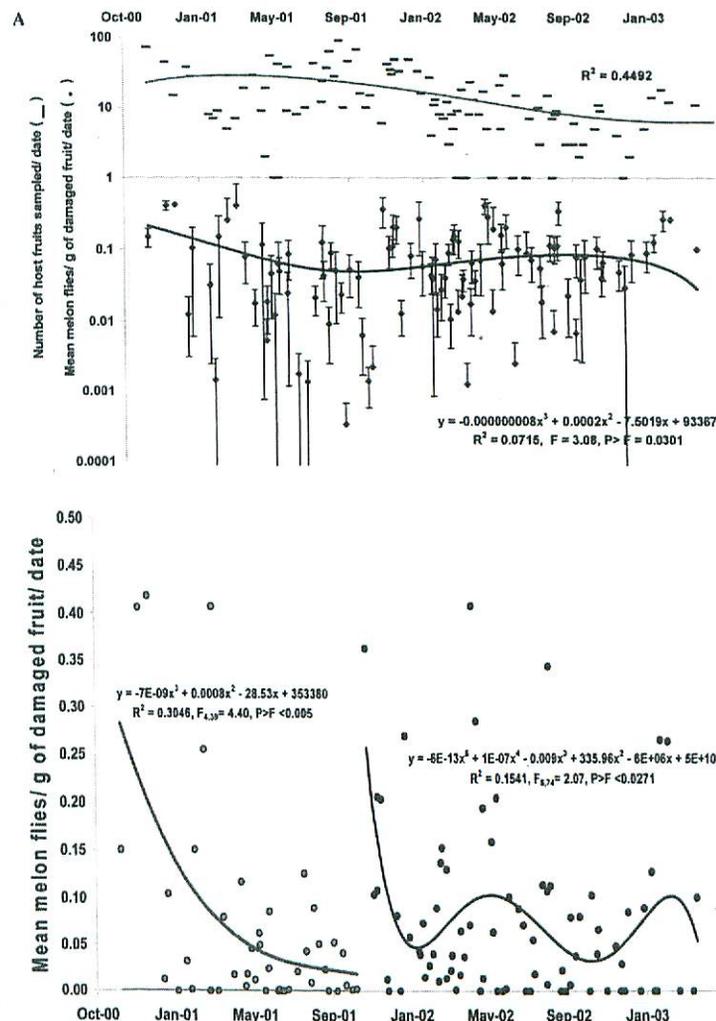


Fig. 9(a). A. The number of fruits sampled and means \pm SEM of melon flies recovered per gram of damaged host fruit in the Kamuela grid is graphed over time. A 3rd order polynomial model is fitted to this data. Although the variability is large, there is a significantly negative trend over time. (Note that the 0 values are not displayed in the logarithmic graph, but are included in the calculation of the regression.) (b). The same date is graphed with zeros included, and two models are applied. First year of data displays a much stronger negative correlation than the second year.

Table 2. Nonparametric nonlinear trends in mean number of melon flies/gram of damaged fruit from 22 Aug. 2001 to 21 Jan. 2003 showing negative trend in wild and garden host plants.

Host specie	Source of Plants a	Linear trend b	Spear-man's R c	Probability > IR	Observations (n)	Overall mean no. melon flies / g
Cantaloupe	All farms	-	0.01919	0.8021	173	0.017 ± 0.006
Crookneck squash	All farms	+	0.02818	0.7286	154	0.093 ± 0.017
Watermelon	All farms	+	0.01373	0.8663	153	0.017 ± 0.008
Cucumber	Gardens > farms	+	0.07658	0.6255	53	0.055 ± 0.019
Zucchini squash	Farms > gardens	+	0.19505	<0.0001	648	0.055 ± 0.006
Pumpkin	Gardens > farms	-	0.06530	0.0508	895	0.101 ± 0.010
Toghan squash	Wild patches < gardens	-	0.34486	0.0056	63	0.003 ± 0.002
Wild squash varieties	Wild patches > gardens	-	0.52594	<0.0001	95	0.069 ± 0.025
Wild bitter melon	Wild patches > gardens	-	0.68737	<0.0001	42	0.067 ± 0.067

^athe symbols indicate that one type of source host is more (>) or less (<) prevalent than the other.

^bRegression trends were based on Pearson's product moment correlations.

^cSpearman's nonlinear correlations do not indicate whether the trend is negative or positive, but these gave higher R values suggesting that the trends were not linear.

time. It should be noted that zucchini was the only cucurbit crop that went from a seasonal crop to continuous year-round production during the period covered by these regressions. Therefore, early fruit samples of zucchini may not have been as thorough as samples taken during full production.

In the commercial farms, there were large numbers of fruit from which to select the damaged fruit. In contrast, the wild and garden patches often had limited numbers of fruit. Early in the suppression program, these were usually highly infested. However, as the melon fly population declined, the likelihood increased that the samplers would select fruit with damage that was not caused by fruit fly. Given that these data include only samples of visibly damaged fruit, it is surprising that it was possible to detect significant change in flies/g of fruit in any crop.

Looking at the actual percentage of all collected fruit samples that were infested, there is a negative trend out to 21 Oct. 2003 (Fig. 10). Between 2000 and 2001, mean infestation in the collected fruit was $50.6 \pm 4.9\%$ per sampling date. In the fall of 2003, the final two collections each averaged $12.50 \pm 0.06\%$ infestation (Fig. 10).

The addition of presence-absence sampling between August 2002 and August 2003 provided an estimate of the actual percentage of all fruit that were infested. This later sampling regime started well after the major reduction in fruit infestation had already occurred in 2001. Nevertheless, the weak correlations derived from this presence-absence data during this year suggested that there was a slight decline in the number of fruit that were actually infested (the model indicates an average infestation level of <20%, Fig. 10.). Fruit emergence data were not taken intensively from melon fly hosts after 8 April 2003. Bait spray, male annihilation, and sanitation were still being applied for control of Mediterranean and oriental fruit fly throughout this period, but sterile fly releases were suspended on 18 Dec. 2002.

Correlations between infestation and the applied suppression techniques are given in Table 3. Parasitoid augmentation is not included because of the minor effect of the wasps on the population of flies. A multiple regression analysis of four control techniques was correlated to percent infestation ($F = 6.89$; $df = 4,66$; $P < 0.0001$) and indicated highest correlation to GF120 applications ($F = 11.0$; $df = 1,66$; $P = 0.0015$) followed by cue lure trapping ($F = 8.97$; $df = 1,66$; $P = 0.0039$). Male sterile fly releases were also correlated ($F = 4.23$; $df = 1,66$; $P = 0.0438$), but the correlation to sanitation as measured by flies emerging in augmentoria was weaker ($F = 3.33$; $df = 1,66$; $P = 0.0724$) because of the large variation of fly emergence in the augmentorium. To illustrate the relationships graphically, Fig. 11 gives the sample means and best fit regressions for the various

control techniques, plotted with the percent of infested fruits (combining both fruit sampling techniques). The 5th order polynomial ($y = -1E^{-1}x^5 + 2E^{-06}x^4 - 0.1442x^3 + 5381.7x^2 - 1E^8x + 7E^{11}$; $R^2 = 0.2901$; $F = 15.28$; $df = 1,191$; $P < 0.0001$) fitted to the infestation data, shows a distinctly negative trend out to 3 June 2003. The combined effect of the suppression five techniques (parasitism is not shown) led to a significant 4-fold reduction in fruit infestation.

Discussion

The combined suppression activities of the USDA and the growers of Kamuela did decrease the population of melon fly dramatically in the first year and maintained that low level into subsequent years of the program (Vargas et al. 2003). There was an increase in population when the USDA curtailed some of the suppression activities. However, by resuming SIT and re-establishing a bait spraying regime, the USDA team probably contained the east grid out-break of melon flies in 2003. It is likely that such a large increase in population would have led to increase elsewhere in the surrounding hosts, and, although the increase occurred in the off-season, cucurbit hosts are available to a lesser extent throughout the winter months. Therefore, it is apparent that the growers were able to contribute substantially to suppressing fruit fly population increase on their farms. Nevertheless, were it not for the efforts of the USDA staff, those farmers would have faced continuous incursion from melon fly population build-up in areas surrounding the Lalamilo Farm Lots,

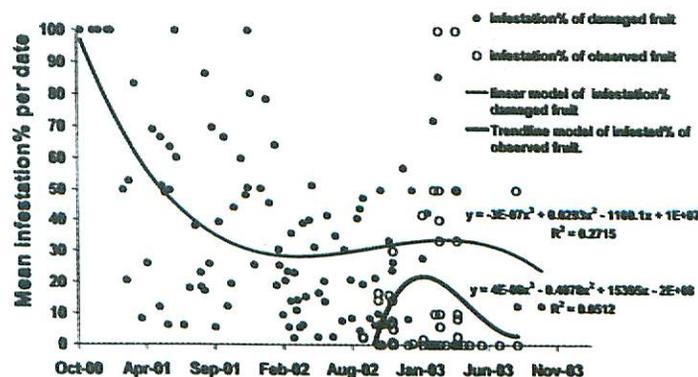


Fig. 10. The percentage of sampled, damaged fruit that was infested is graphed as means over time. This best-fit polynomial regression model is compared with the trendline for infested percentage of all observed fruits in 2002–2003.

Table 3. Correlations of each of four suppression techniques with fruit infestation over the period of melon fly suppression.

Pearson's product moment correlation ^a	Dependent parameter	Date	Applied ml GF120	Flies caught in augmentoria	Sterile males released	Spearman's correlation for no. CL traps ^b
R	Infestation%	-0.3035	-0.1517	-0.2219	-0.4345	0.7167
R squared		0.0921	0.0230	0.0492	0.1888	0.5136
Prob > R		<0.0001	0.0886	0.0424	<0.0001	0.0298
n		189	127	84	82	9

^aPearson's product moment correlations are parametric linear analyses with infestation% as the dependent variable plotted against levels of each treatment individually.

^bSpearman's nonlinear rank correlation gave higher R values for traps deployed, but the test does not indicate whether the correlation is positive or negative. Increasing number of traps was associated with decreasing infestation%

precisely because there was less grower cooperation in using fruit fly suppression techniques in those areas.

Subsequently individual growers have had success using the techniques to manage fruit flies on small farms in other areas of the Big Island (Jang et al. 2007). Therefore, the objectives of the program were met in terms of the growers' ability to implement suppression on their own farms, but the concept of area wide suppression is relative to the number of growers participating, and the surrounding fruit fly host population. The greatest success is achieved when the level of grower cooperation in an area is high, or the grower is isolated from off-farm populations of fruit flies.

This leads to the larger question of how to implement a suppression program in a tropical island which consists of mostly small farms, residences, and unmanaged areas, all of which may contain fruit fly host plants. In Hawaii, melon fly is the most manageable of the established fruit fly species of economic importance because there are fewer host plant species than those of the other major tephritid species present in the State. The host range of *B. cucurbitae* is confined primarily to cucurbit and solanaceous hosts (Dhillon et al. 2005). For this species, the concept of concentrating male lure traps around host areas is an effective approach to suppression when also used to coordinate the application of other suppression techniques (e. g. sanitation, bait sprays and biological control) based on adult fly counts in each location. Similarly, *B. latifrons* (of lesser economic importance in Hawaii) is also restricted to a few hosts and probably would benefit more from a targeted trapping system rather than a uniform distribution of traps on a grid. Although Mediterranean fruit fly has many fruit hosts (Liquido et al. 1990 and 1998), in Hawaii, in many areas, it is suppressed by the presence of oriental fruit fly (Bess

1953, Haramoto and Bess 1970). That competition made suppression of the Mediterranean fruit fly easier in Kamuela, Hawaii than in Kula, Maui (McQuate et al. 2005, Vargas et al. 2001) where the population of *C. capitata* exceeded that of *B. dorsalis*.

This project's manager did not consider targeted trapping to be a technique likely to suppress oriental fruit fly, and male annihilation traps were subsequently deployed on a high-density grid. Nevertheless, the areas of increased trap density were chosen based on oriental fly population density derived from trap monitoring data deployed on the original 40-km² grid. Therefore our data suggest that it is efficient to use the monitoring trap catch to determine the deployment of male lure traps in areas where the vegetative hosts are plentiful, and where the species of fly is not ubiquitous.

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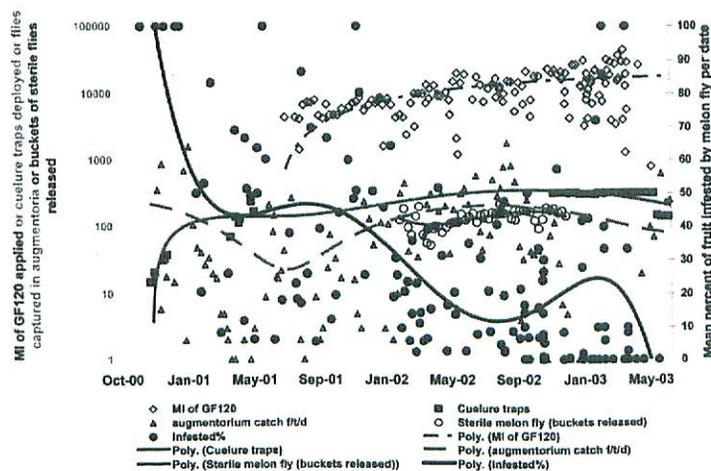


Fig. 11. The combined data for both methods of computing infestation is graphed against the levels of application of the various suppression techniques (except parasitoids). Polynomial best-fit models are derived for each treatment to show the relationship between suppression and fruit infested percentage over about 2.5 yr of sampling.

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