Development of the Sterile-Insect Technique on the Island of Lanai, Hawaii, for Suppression of the Mediterranean Fruit Fly[2]

ERNEST J. HARRIS, ROY T. CUNNINGHAM, NORIMITSU TANAKA, KIICHI OHINATA,[3] and WILLIAM J. SCHROEDER[4]

ABSTRACT

Sterile Mediterranean fruit flies were released on the island of Lanai in a pilot development program to demonstrate the ability of the laboratory strain to suppress the wild population. Sterile flies were released as adults or pupae from the air or from sites on the ground. Utilization of different release methods provided flexibility in scheduling releases to overcome problems of wild fly distribution, terrain and weather. The sterile flies suppressed the wild population 99% below the pre-treatment level for 6 months, as evidenced by reductions of larval infestations in guava. The sterile-insect release method was effective in spite of entry of gravid females from the upwind island of Maui, and was shown to be well-suited for eradication of localized populations of the Mediterranean fruit fly in the Hawaiian Islands.

The Mediterranean fruit fly (medfly), *Ceratitis capitata* (Wiedemann), is a serious pest of tropical and subtropical fruits. Since this insect can be economically mass reared in the laboratory, numerous experiments have been conducted with sexually sterile releases to suppress field populations. The results have been variable depending on the size and type of experiment conducted, but a number of scientists have provided scientific proof of the feasiblity of the method. In large-scale tests, Rhode et al. (1971), Cirio and de Murtas (1974), Simon (1974), and Cheikh et al. (1975), reported encouraging results in the control of established populations of the medfly with sterile releases only or with sterile releases in combination with other methods. None of these programs achieved eradication of the medfly and research is still in progress to develop safe, economical sterile-insect release techniques as alternatives to conventional and food-bait sprays. Although the aerial application of bait sprays is an effective, economical method for controlling the medfly in large commercial fruit production areas of hundreds of square kilometers (Steiner et al., 1961; Stephenson and McClung, 1966), these bait sprays have undesirable side effects; they may kill nontarget organisms (Ichinohe et al., 1977), pollute the environment, and damage automobile finishes (Ohinata et al., 1967). Thus, alternatives are desirable for use in urban areas.

Our research program in Hawaii for many years has been oriented toward the development of novel approaches for detection, suppression, and eradication of (1) incipient outbreaks of the medfly from the mainland states, and (2) populations established in Hawaii. Progress made in the development of new methods of handling, irradiating, and releasing sterile medflies in a pilot test carried out on the Island of Lanai, Hawaii was reported earlier by Harris et al. (1975). The present study reports the results of the 1973–75 medfly sterile release pilot test which was tailored for application in diverse action agency eradication programs.

[1]Tropical Fruit and Vegetable Research Laboratory, USDA-ARS, Pacific Basin Area, Honolulu, Hawaii 96804.

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[3]Deceased.

[4]Present address: USDA-ARS, Apopka, FL 32703.

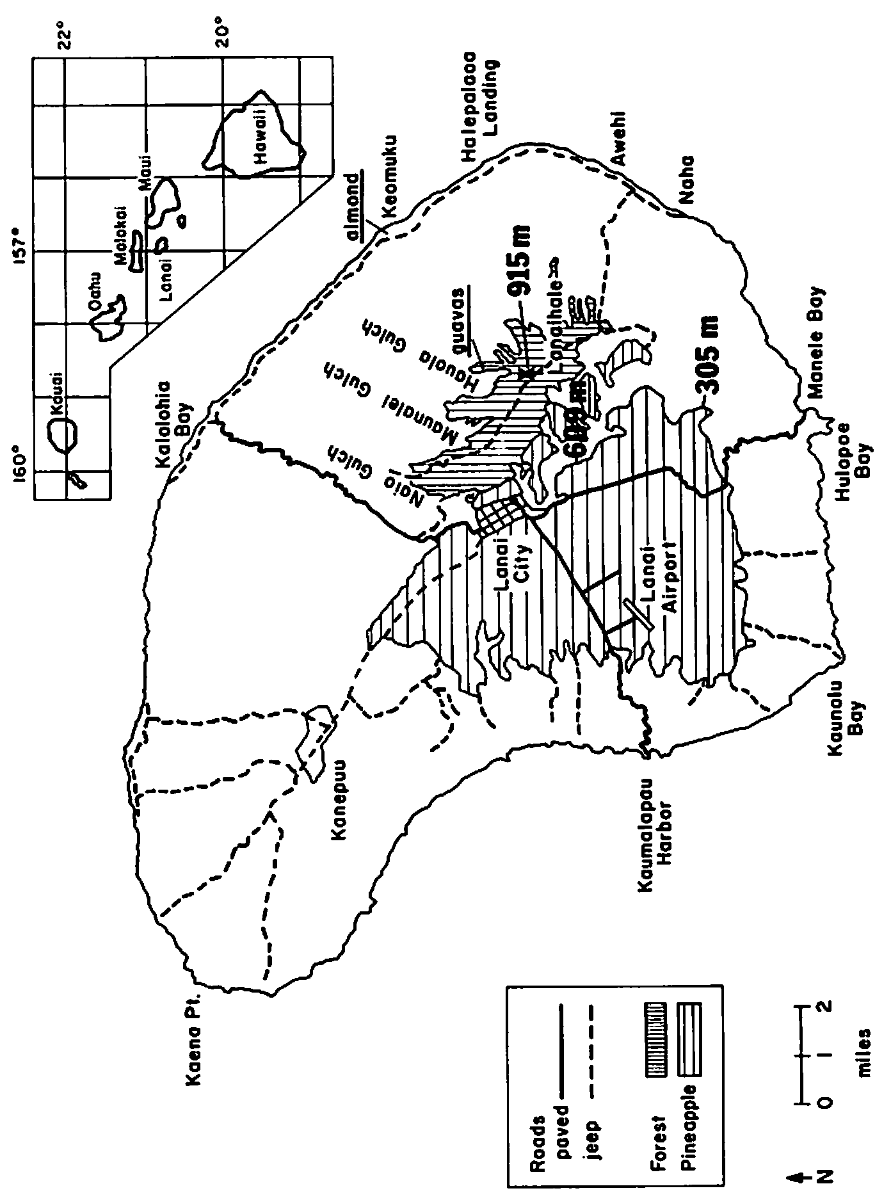

FIGURE 1. Map of Lanai showing the topographic features of the island and the distribution of roads, forest, pineapple, guava and almond (tropical almond = false kamani).

We chose a study site within the budgetary and logistical capability of available laboratory resources that would provide a wide range of operational problems encountered in an action agency eradication program. One constraint was that no control area comparable to the release area was available and, second, there was consistent immigration of medflies from Maui to Lanai and we recognized from the outset that eradication per se would not be possible. Therefore, our control was in time. We compared medfly population levels and fruit infestation rates before we began our study with those found during and after the study, with the objective of measuring the level of suppression that occurred during the period that sterile flies were released.

MATERIALS AND METHODS

Geography of Lanai. The island of Lanai (Fig. 1) covers 381 km² and has a population of 2500 people, most of whom live in Lanai City (1.29 km²). The elevation range is 13–65 m in the seashore areas, 305–610 m in the central plateau, and about 915 m at the central peak. The climate is arid, with a median annual rainfall ranging from 25.4 to 88.9 cm (L.S.B. 1967). Medfly host plants, mostly guava, *Psidium guajava* L., and false kamani, *Terminalia catappa* L., are found localized in habitats mainly in a 31-km² area with highest rainfall and elevations greater than 305 m and near the seashore, respectively. More than 6475 ha are planted in pineapple in the central plateau. Cultivated host plants are also found in Lanai City, Maunalei Gulch, and at a few inland or seashore locations of the following types: common guava, *P. guajava* L., lemon guava and strawberry guava, *P. cattleianum* Sabine; loquat, *Eriobotrya japonica* (Thumb.) Lindl.; Surinam cherry, *Eugenia uniflora* L.; orange, *Citrus sinensis* (L.); peach, *Prunus persica* (L.) Batsch; mountain apple, *Syzygium malaccense* (L.) Mersill and Perry; rose apple, *E. jambos* L.; coffee, *Coffea arabica* L.; and Jerusalem-cherry, *Solanum pseudocapsicum* L.

Fruit Fly Survey: Pretreatment, Monitoring, and Evaluation. Plastic traps (Steiner, 1957) were widely distributed over Lanai at the rate of ca. 1 per 5 km² in 1970 to obtain pretreatment information on medfly populations. Initially, the traps were baited with 2 ml of a mixture of trimedlure (Beroza et al., 1961) and naled (30%) applied on a 2.5-cm cotton dental roll. Subsequently, the lure along was used on the wick, and the toxicant was supplied in a 2-cm strip of plastic dog collar impregnated with 20% DDVP or naled. The survey program was expanded in the fall of 1972 by an increase in the number of trap sites from 1 per 5 km² to 1 per 2 km². The traps were serviced weekly or biweekly. We checked fruit infestations on Lanai by collecting fruits at weekly intervals from locations where fruits were in production. The fruits were held in fruit holding boxes (Tanaka, 1969) for 3 weeks. Flies and parasites reared from the fruit were identified and recorded. Also, 20 host density stations were established within a 31-km² area at the rate of 2 per km² and checked at monthly intervals for estimations of the relative abundance of guava fruits over time.

The pretreatment survey was followed by the monitoring phase after the releases of sterile medflies began, and the evaluation phase after releases were terminated. The transition was gradual, and the phases overlapped. The entire program was completed within ca. 4 years (1973–76).

Sterile-Fly Releases. Three bait-spray treatments were applied to ca. 10 km² of guava at 600- to 1000-m elevations in the central plateau area between Aug. 1, 1973 and Sept. 18, 1973, in an attempt to suppress wild flies to a low level and follow-up with sterile-fly releases to achieve maximum suppression. However, we were unable to rear a sufficient number of sterile flies early enough to take advantage of the suppression of wild flies by the bait sprays. We nevertheless decided to terminate the bait sprays and rely solely on sterile-medfly releases to achieve our goal.

From May 1973 to Jan. 1975, sterile medfly pupae were shipped to Lanai in polyethylene plastic bags (Tanaka et al., 1972). All pupae were irradiated with 15 krad. Flies were maintained in an atmosphere of nitrogen during irradiation to improve their sexual competitiveness (Hooper, 1971; Ohinata et al., 1978). Weekly releases of pupae were made from 4-liter plastic release buckets. The buckets tapered from 15 cm in diam. at the top to 12 cm in diam. at the bottom, had eight 3-cm holes opened along the side (through which flies could escape), and had three drainage holes in the bottom. A nesting inner bucket held the pupae, which were covered with loose bundles of excelsior or straw to provide resting surfaces on which the flies could expand their wings upon eclosion. A maximum of 150 to 250 ml of pupae (ca. 10,000–16,000 flies) was placed in each bucket to minimize injury from overcrowding during emergence. During the peak of the program, ca. 600 buckets were distributed over 31 km^2 of the highest guava production areas and also in an additional 10-km^2 coastal strip (Fig. 1). These buckets were distributed along jeep roads and hiking trails.

Another technique aimed at improving sterile fly coverage involved aerial distribution of naked pupae. This system implemented in June 1974 was used in twice-per-week flights to cover ca. 13 km^2 of inaccessible Lanai Hale, marginal guava host areas. In another method developed for aerial release of flies, fed adults were immobilized by chilling, irradiated with 10 krad in air, and packed in straw-filled 12.09-kg paper bags at rates of 6,000 to 25,000/bag (W. Schroeder et al., unpublished data). The single-engined aircraft used for the releases limited this operation to 300 bags of adults in one flight per week. In an auxiliary adult-release method, batches of ca. 65,000 flies were allowed to emerge in 208-liter plastic garbage bags secured to screen frame tops (Schroeder et al., 1973) in which the flies were provided with sugar, protein, and water (Keiser et al., 1969). One or 2 days after adult eclosion, the bags of flies were transported by jeep to release sites in gulch areas.

The pupae used in ground bucket releases were marked with Calco Blue dye at the rate of 4 g/liter of pupae (Steiner, 1965); the adults used in aerial releases in paper bags were marked with Tinopal (Schroeder et al., 1972) at the rate of 2 g/liter of pupae; and the adults used in ground releases were marked with Calco Orange at the rate of 4 g/liter. The pupae for broadcast releases could not be effectively marked by this external dye system, so we could not differentiate wild flies from unmarked flies broadcast as pupae. However, we continued to mark sterile flies for 4 additional months to monitor distribution and mixing of marked with unmarked flies until October 1974, when all marking was discontinued.

Population Estimate. In December 1973 we made a release of adult flies that had been allowed to feed for 3 days after emergence while confined in paper bags. Approximately 270,000 males and an equal number of females were released from 10 sites scattered in the most productive guava areas of Lanai. Counts of the bag contents after the release showed that over 93% of the pupae yielded good fliers (Ozaki and Kobayashi, 1981). Male flies caught in the trimedlure-baited traps scattered throughout the area were collected weekly. We subsequently examined them to determine whether they were dyed (lab flies) or undyed (wild flies). Using the Lincoln (1930) Index method, we estimated the wild male population on Lanai to be 64,000 males (total of 128,000 flies). We expected this relatively small population to be within our capacity to overflood massively enough to significantly reduce reproduction.

RESULTS AND DISCUSSION

During the first 8 months of the program in 1973, 144 million sterile flies were released as pupae in ground release buckets. The recovery rate of males in survey traps is an index of survival of released flies. In 1973 the recovery rate of males released as pupae from buckets was only 0.01% (Table 1). The low recovery was attributed to poor survival of flies due to the fact that when the releases were started in May 1973, Lanai was in its worst drought on record. In November 1973 the drought broke, and by early 1974 the drought had been supplanted by wet conditions. Sterile fly production, which had averaged ca. 5 million flies/week in 1973, was increased to ca. 15 million/week in 1974. Of 758.2 million pupae shipped to Lanai in 1974, 59.2% were released from ground release buckets, 21% were released aerially as adults in paper bags, 15.8% were released aerially as naked pupae, and 4% were released on the ground as adults from large cages made of plastic garbage bags.

Of flies irradiated as adults and released aerially, 0.19% were recovered in traps. The main purpose of this release method was to distribute flies into inaccessible, untrapped areas. Twenty six million flies were released into high fruit infestation areas as fed adults from plastic garbage bags, of which 0.48% were recovered in traps.

The recovery rate from both the adult ground and aerial release systems was about 0.15%. Cunningham et al. (1971) showed that the recovery of medflies broadcast as pupae was only 50% of that of medflies released as bagged adults. Our data showed that the recovery of broadcast pupae on Lanai averaged only ca 10% of that of medflies released as adults. The reduced recovery rates from broadcast pupae compared to the aerial release were probably a result of higher mortality of these pupae from predation and mechanical injury.

Ratios of marked to unmarked medflies remained near 10:1 throughout the release period in 1973 (Table 1). When sterile fly production was increased in 1974,

TABLE 1. Monthly total catches of male Mediterranean fruit flies trapped on Lanai.

	Marked										
	Calco Blue (Previously ground released from buckets)		Tinopal (Previously aerial released as naked adults)		Calco Orange (Previously ground released from plastic bags)	Unmarked		Overflooding ratio Marked:unmarked		Percentage recovery Marked flies	
Month	1973	1974	1973	1974	1974	1973	1974	1973	1974	1973	1974
Jan.		8,967		149			123		74:1		0.03
Feb.		19,365		9,427			380		76:1		0.06
Mar.		57,101		24,623	3,863		820		104:1		0.14
April		84,388		38,615	643		1,271		97:1		0.17
May		10,5091		48,840	7,021	24	8,189		20:1		0.28
June	2,314	54,445		29,042	13,778	144	1,772[a]	16:1	55:1	0.02	0.21
July	1,044	41,653		10,447	3,974	116	674	9:1	[b]	0.01	
Aug.	1,988	91,316		24,042	8,120	170	3,527	12:1		0.01	
Sept.	3,058	76,905		33,035	6,892	295	5,769	10:1		0.01	
Oct.	1,684	14,974		8,301	544	119	84,898[b]	14:1		0.01	
Nov.	1,160	1,732		298	6	126	102,744	9:1		0.004	
Dec.	8,335	161	533	56		856	50,340	10:1		0.05	
Total	19,583	556,098	533	266,875	44,841	1,850	261,007			0.01	

[a]Pupal drops started.

[b]Ratio counts terminated; flies released unmarked thereafter to enhance their dispersion and competitiveness in the field.

TABLE 2. Summary of Mediterranean fruit flies reared from fruits collected in key habitats on Lanai.

Locality	Varieties of Fruits	1973 Fruit No.	1973 Fruit wt(kg)	1973 *capitata*	1974 Fruit No.	1974 Fruit wt(kg)	1974 *capitata*	1975 Fruit No.	1975 Fruit wt(kg)	1975 *capitata*	1976 Fruit No.	1976 Fruit wt(kg)	1976 *capitata*
Basin	Common guava	4212	164.1	1980	9815	733.5	6	13791	686.8	33	3100	157.5	456
Bench fields	Common guava	284	12.6	24	7853	193.8	28	7167	333.7	7	1120	63.6	33
	Strawberry guava	0	0	0	0	0	0	1371	5.8	0	1665	12.1	19
Keomoku Beach	Common guava	0	0	0	125	9.01	0	0	0	0	50	2.4	0
	False kamani	1838	28.3	400	8764	289.9	565	7736	177.6	165	2038	47.6	509
Lanai City	Coffee	0	0	0	70	0.14	0	2563	5.9	5	825	2.3	23
	Common guava	200	8.3	1	385	81.3	6	7833	434.1	6	1288	71.2	67
	False kamani	0	0	0	0	0	0	251	5.7	5	0	0	0
	Jerusalem cherry	0	0	0	100	0.3	0	0	0	0	0	0	0
	Lemon guava	0	0	0	500	4.53	0	0	0	0	0	0	0
	Loquat	50	0.1	0	199	2.44	1	431	6.3	0	145	27	0
	Mango	0	0	0	0	0	0	34	5.1	0	0	0	0
	Orange	0	0	0	93	16.5	2	0	0	0	0	0	0
	Peach	0	0	0	72	2.3	0	138	2.4	0	259	6.3	6
	Rose apple	0	0	0	211	7.64	0	209	2.93	2	0	0	0
	Strawberry guava	0	0	0	597	5.2	0	1497	15.3	0	577	3.5	0
	Surniam cherry	100	0.79	0	173	1.44	0	163	1.1	0	385	5.1	0
Lanai Hale	Common guava	810	28.3	13	6856	447.4	66	4239	203.5	1	420	17.8	83
	Strawberry guava	0	0	0	3528	508.4	1	119	1.85	0	530	9.0	40

overflooding ratios ranged between 9:1 and 104:1 and were reflected by reductions in fruit infestation (Fig. 2) and Table 2.

As a consequence of the drought in 1973, there was no spring guava crop. However, the guava crop was normal in 1974 and 1975. The correlation of guava number and size with the amount of rainfall was demonstrated. For example, a sample of 12,300 guavas from several areas taken in the period of drought from July to September 1973 had an average weight of 43 g/fruit, while an equivalent sample from the 1974 crop which had ample rainfall had an average weight of 73 g/fruit. In 1975, the average weight of 58 g/fruit was intermediate between those of the 2 prior years as was the rainfall. The quantity and quality of fruits were adequate to support a large medfly population in the absence of suppression by the sterile medflies.

A decrease of 99% in the medfly infestation rate island-wide (Fig. 2) was achieved by August 1974 in guava even though breeding material and food were abundant. The host density stations (Table 3) showed prolonged fruiting in 1974 and more fruit in 1975 than in 1974. In December 1974 and January, February, and May 1975, the infestation rate was zero; only 10 medflies were reared from 21,011 guavas and 35 from 2810 false kamani during this 6-month period. Table 2 summarizes the results obtained from holding and rearing medflies out of fruits collected in the key habitats on Lanai. The areas producing the most guavas and medflies were the basin, Lanai Hale, and the Bench fields. Ninety-eight percent reductions in medfly infestations in the Basin in 1974 and 1975 compared with 1973 is quite evident. In Lanai Hale and the Bench fields 92 and 70% reduction in guava infestation was achieved in 1975 compared with 1973 where sterile naked pupae drops were made in combination with other methods. In Keomoku only 50% reduction in medfly infestation was achieved in 1975. The fruits cultivated in yards in Lanai City were lightly infested by the medfly and did not contribute significantly to the medfly population on Lanai. The availability of fruit in Lanai City was localized and the phenology of fruiting highly variable in comparison with extensive distribution and more persistent fruiting of guavas in the highest rainfall areas.

In the narrow 10-km^2 coastal strip on the north side of Lanai facing Maui, summer homes are present among dry Kiawe, *Prosopis pallida*, shrubs. A cluster of six false kamani trees grow in one small area at Federation Camp. A high release rate of sterile flies was maintained in this seemingly inhospitable area; yet more medflies were reared from the fruits in this small area in 1974 and 1975 than from fruit in the more favorable and larger guava-producing areas (Fig. 1). We believe that the higher infestation rate in these kamani trees was a result of the egg-laying activity of a small number of gravid females that were blown over from the upwind island of Maui. These females may have failed to find other hosts along the barren seashore and concentrated on these kamani trees. The dry and windy inhospitable area between the narrow coastal strip and the guava areas probably inhibits medfly movement to the higher and more favorable host areas.

Catches from traps placed along the shore line on the neighbor islands upwind of Lanai showed that medflies are caught throughout the year on Maui as well as on Lanai. By contrast, only one medfly (female) was caught on Molokai in 1974. It is notable that Lanai is 13–16 km downwind of Maui, and because Maui has an abundance of breeding hosts, medflies could be constantly transported by wind currents to Lanai. This phenomenon was confirmed by the release of marked medflies on Maui and Molokai. A single dyed fly was recovered on Lanai from each of two releases of relatively small numbers (30,000) of adults on Maui (S. Nakagawa et al., unpublished data).

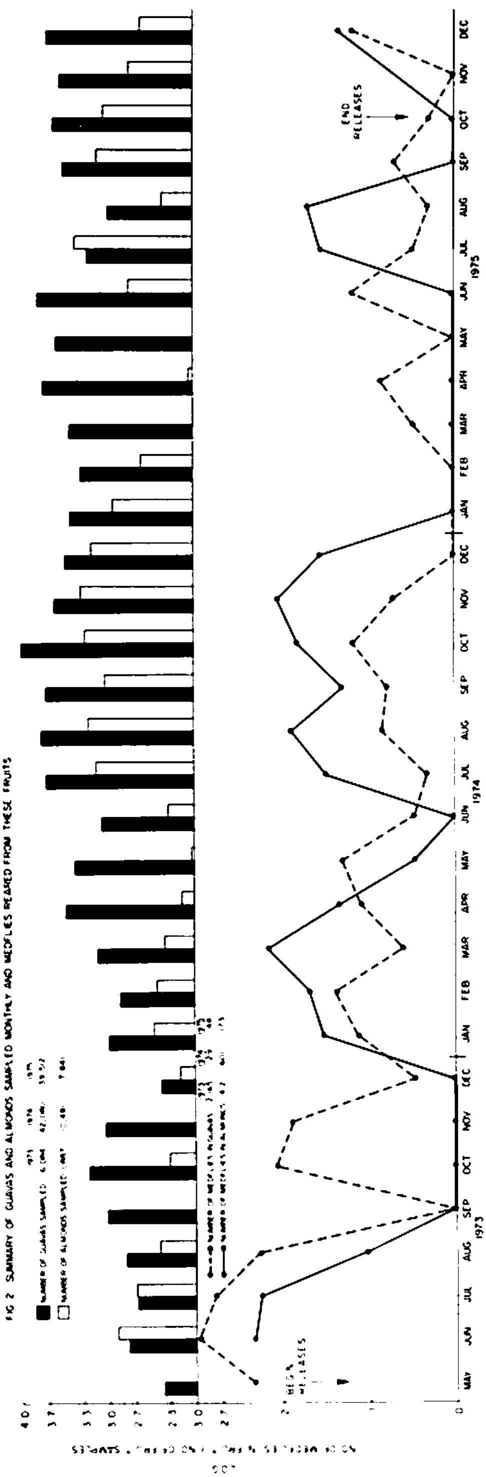

FIGURE 2. Summary of guavas and almonds sampled monthly and numbers of medflies reared from these fruits (tropical almond = false kamani).

TABLE 3. Summary of guava fruit density counts at 20 stations on Lanai and rainfall and temperature recordings in Lanai City.

Month	Guava fruit density count[a]			Total monthly rainfall (In.)			Average monthly temperature (°F.)		
	1973	1974	1975	1973	1974	1975	1973	1974	1975
Jan.	0	34	145	0	11.28	10.52	0	67.7	0
Feb.	0	4	177	0	2.87	6.21	0	67.1	63.5
Mar.	0	82	205	0	5.00	1.87	0	0	0
Apr.	0	127	180	0	1.65	2.19	0	68.3	68.1
May	0	10	318	2.44	2.26	0.37	68.0	69.4	0
June	17	16	144	0.42	6.44	0.44	69.8	69.5	69.7
July	—	393	68	0.22	3.60	1.47	71.1	70.1	70.4
Aug.	225	681	20	2.32	0.23	0.17	72.0	71.0	71.1
Sept.	759	514	403	1.44	8.71	0.97	71.2	71.5	71.0
Oct.	95	242	401	1.23	3.82	0.34	70.8	71.4	70.1
Nov.	72	230	536	8.59	2.35	2.11	69.8	67.7	0
Dec.	52	98	229	6.90	0.94	1.09	67.2	0	0

[a]Based on estimates of guava abundance in 20 plots.

As indicated previously, dye marking of medflies prior to release was discontinued in June 1974 (Table 1) to enhance their dispersion and competitiveness in the field. When the number of unmarked flies began to increase greatly, use of overflooding ratios to evaluate program progress was valueless. We were prepared to initiate the release of only marked flies again if fruit infestation rates had resurged. Since some toxicity is associated with dye usage, the improved quality of the unmarked sterile flies resulted in better survival than with those flies used in 1973. We felt that the improved quality of the unmarked sterile flies compensated for the loss of our ability to track and monitor the overflooding ratios. All ground releases were stopped in February 1975. After that time, suppression was maintained at the 99% level with the aerial broadcast of ca. 2 million pupae/week, despite the continuation of favorable breeding conditions. All air drops were discontinued in October 1975. The lower rate of release in 1975 was adequate to maintain suppression at a low level until the program was terminated.

Oftentimes, the philosophy in sterile-insect release programs is to make releases when conditions are unfavorable for the wild flies, or when their numbers are reduced, such as following a drought or typhoon, so as to give the sterile insect an advantage. The climate on Lanai was harsh and quite variable but was generally favorable at higher elevations. Our fruit counts and fruit collections showed that perhaps adverse conditions in the field affect released flies more than wild flies because concentrations of sterile flies may deplete local food resources. Under these conditions the sterile flies are at a disadvantage because they may not be as efficient as the immigrant wild flies in finding food resources. Subsequent releases therefore could further decrease available food and cause high mortality of sterile flies due to insufficient food (Monro, 1966). This problem is especially acute for medflies released as pupae. The release of sterile flies as fed adults is thus recommended when food resources in the field are limited. If pre-release feeding is not feasible, ground release of fed adults in "hot spots" is an effective alternative. Our experience showed that further study is needed to determine when to begin an eradication program so as to fully utilize the beneficial effects of climatic and other natural factors and to minimize their adverse effects on the survival of sterile insects.

The salient features and limitations of methods of releasing sexually sterile medflies are summarized in Table 4. The combination of methods we used consisted predominately of ground releases from Lanai buckets and aerial broadcast of pupae. This combination of methods was the best compromise for the conditions on Lanai. The release method or combination of methods chosen to release medflies in an action agency program should, insofar as possible, be determined by the climatic and natural conditions existing in the areas where the sterile medflies must compete with their wild counterparts.

Our laboratory strain had been reared through more than 200 generations when the program was started. Improvements, especially irradiation in an atmosphere of nitrogen, of all medflies scheduled for release, bulk handling, and effective release methods undoubtedly contributed to the success of the program; however, the lab strain still apparently retains genes that enable it to adapt to field conditions and compete with wild flies. Eradication would probably have been achieved had the island of Lanai been completely isolated and had there been no immigration of medflies from Maui.

TABLE 4. Summary of the salient features and limitations of the methods used to release sexually sterile Mediterranean fruit flies on Lanai.

Method of release	Salient features and limitations
1. Ground release from Lanai bucket	Method is convenient for uniform distribution of marked flies; assures emergence of adults over time in hot spots. Method can be easily integrated with trap and fruit monitoring system. Emerging flies may be subjected to high mortality by predators aggregating around release sites.
2. Aerial release of chilled adults	Method convenient for handling and releasing adult flies. Method permits even distribution of fed adults to mate with wild flies. Release flies subject to predation before they recover from chilling and mortality from landing on hard surfaces such as roads and roofs of buildings.
3. Aerial release of naked pupae	Method is by far the easiest for distribution of large volumes of flies by aircraft, especially into roadless, inaccessible areas because of convenient procedures for accurate metering of the pupae. Method has the added advantage of easy control of flow rate and distribution pattern of free falling pupae which drift very little during fall. However, pupae and emerging flies subject to heavy losses from predation; losses estimated as high as 85-90 percent. Method also requires more time for emerged flies to become sexually mature, and released flies cannot be marked with florescent dyes.
4. Aerial release of adults in paper bags	Convenient method to distribute fed adults sexually mature and ready for mating, by airplane without chilling. In an emergency, method can be used for ground release of flies. Volume of space occupied by bags creates a limitation in the number of flies that can be released from small planes as compared with chilled adult system. In some situations, the bags may cause a pollution problem.
5. Ground release of adults from garbage bag	Convenient method to distribute fed adults ready to mate into hot spots to fill gaps in the aerial release program. When excess flies are produced, this is a good method with which to distribute flies. Method not feasible for use in remote inaccessible areas.

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