FORUM

Sensitivity of Detection Trapping Systems for Mediterranean Fruit Flies (Diptera: Tephritidae) in Southern California

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ABSTRACT Release–recapture studies were conducted in southern California to determine the probability of capturing Mediterranean fruit flies, *Ceratitis capitata* (Wiedemann), in standard trapping arrays used to detect and delimit introduced populations. Two tests were conducted in a 10.4-km^2 area of Orange County that contained a total of 40 trimedlure-baited Jackson traps (10 traps per 2.6 km^2 [1 square mile]). Radiosterilized flies were marked with one of four colors and released at four different distances from each trap. Numbers of flies released at each point were adjusted so that the nominal density throughout the test area was 25 (first trial) or 12 (second trial) flies per hectare. In both trials, percentage of flies recaptured was ≈0.6% overall and, in general, was related inversely to the distance from the release site to the trap. In other tests, 23–27% of flies were recovered when released in Orange County within 0.26-km^2 plots that contained 100 trimedlure-baited yellow sticky panels. Using results of these and a previously published study, simple mathematical models based on binomial probability theory indicate that arrays of 10 Jackson traps per 2.6 km^2 would detect high proportions of relatively small, stable infestations of *C. capitata* within several generations. Arrays of 1,000 yellow panel traps per 2.6 km^2 essentially would detect all viable infestations within one generation and provide a sensitive tool for confirming eradication after treatment of infested areas.

KEY WORDS *Ceratitis capitata*, trimedlure, release–recapture

EFFECTIVE INSECT-DETECTION systems are essential for preventing the establishment of exotic pests such as the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), in the mainland United States. Surveys for *C. capitata* are included in state and federal exotic pest-detection programs in at least nine southern and southwestern states. In particular, California maintains extensive arrays of sticky Jackson traps baited with trimedlure (a parapheromone that attracts primarily male flies) plus McPhail traps baited with protein hydrolysate or yeast (USDA 1991). These arrays detected infestations of *C. capitata* in California in 1975, 1980–1981, and every year since 1987 (Mitchell & Saul 1990, Miller 1992). Except for ongoing projects, all of these infestations have been declared eradicated.

Trapping systems for detecting *C. capitata* have evolved in response to the practical experience gained in operational programs. In 1980, discoveries of *C. capitata* in California triggered an eradication program that lasted 28 mo and cost an estimated $200 million (Jackson & Lee 1985, Miller 1992). Earlier detection of introduced populations was seen as a way to reduce the length, scope, and expense of subsequent eradications (Jackson & Lee 1985). In response, the density of trap sites in high-risk (i.e., residential) areas of California was increased to 5 per 2.6 km^2 (1 square mile) from previous levels of 0.2 to 1 per 2.6 km^2 (Gilbert et al. 1984, Jackson & Lee 1985). The density of trap sites in greater Los Angeles was increased again to 10 per 2.6 km^2 after an introduced population was thought to have grown and spread to several locations before or during the 1989–1990 eradication program. Other refinements in trapping protocol have included moving trap sites every 6 wk, training trapping personnel in the placement and handling of traps, and keeping traps in or near fruiting host plants (Gilbert et al. 1984, 1991).

Despite these modifications, the sensitivity of detection surveys for *C. capitata* remains poorly understood. Numerous release–recapture studies have been conducted to evaluate the dispersal of *C. capitata* and their responses to lures (Wakid & Shoukry 1976, Wong et al. 1982, Cunningham & Couey 1986, Baker & Chan 1991, Plant & Cunningham 1991). Some of these (e.g.,

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Cunningham & Couey 1986) were designed to provide estimates of the proportions of flies recaptured when released at various distances from traps. However, few of these findings have been translated into estimated probabilities of detecting isolated infestations. Further, most release–recapture studies have been conducted in groves or orchards that are biologically and structurally much simpler than urban and suburban areas such as those in southern California.

Early detection of *C. capitata* populations is becoming increasingly important. California relied heavily on aerial applications of malathion bait sprays in its 1980–1982, 1987–1988, and 1989–1990 eradication programs, but political pressures resulting from perceived environmental, health, and property-damage issues have made that option undesirable. Indeed, more recent eradication programs in California (Los Angeles, 1991–1992; San Jose, 1992–1993; the Los Angeles basin, 1992–1994) have been restricted to limited ground applications of insecticidal baits followed by releases of sterile insects. In addition, controversy over the possibility of an established, low-level population of *C. capitata* in southern California exists, in part, because of differing interpretations of the ability of the trapping system to detect small populations (Carey 1991a, b).

We used release–recapture of sterilized *C. capitata* to assess the probability of detecting a small infestation in a specific area with the current trapping system. We also assayed a high-density trapping grid used to delimit newly detected infestations. Our results and those from an earlier release–recapture study (Cunningham & Couey 1986) were used in simple probability models to estimate the likelihood of detecting populations of different sizes.

Materials and Methods

Source of Flies. Sterile Mediterranean fruit flies were obtained from the USDA–APHIS Hawaii Sterile Fruit Fly Rearing Facility in Waimanalo. The strain was colonized from a Hawaiian wild population and has been in laboratory production for >300 generations. Larvae were reared on a wheat-based diet (Tanaka et al. 1970). Mature larvae were collected in water, drained, and placed in vermiculite. After 48 h, the pupae were sifted out and placed on screen trays at 20°C. Twelve-day-old pupae were marked using 3 g of neon-red fluorescent powder (Day-Glo Color, Cleveland, OH) per liter, which results in a permanent, internal mark within the retracted ptilinum of adults (Schroeder & Mitchell 1981). Marked pupae were sealed into semipermeable plastic bags for at least 1 h to ensure hypoxia. Bags of pupae were then exposed to 150 Gy (15 krad) of radiation from a cesium source, placed in cardboard cartons, and flown to Los Angeles. In Los Angeles, pupae were rinsed with water to remove the majority of the neon-red powder and then were marked a second time using fluorescent powders of different colors. Flies were held at 21–25°C in 0.04-m^3 acrylic cages (1,500–2,500 flies per cage) and were provided with slabs of 15% sucrose in 0.9% agar.

Detection Trapping. Release-recapture tests were run within four contiguous 1.6-by-1.6-km (2.6 km^2 [1 square mile]) blocks in Santa Ana (Orange County), CA. The area was primarily a residential neighborhood of single-family homes. We used the operational detection trapping grid of 10 trap sites per 2.6 km^2 that was in place throughout the area. Employees of Orange County selected the trap sites and placed the traps as part of their routine duties. In accordance with established protocol, traps were placed, whenever possible, in trees bearing ripe fruit that were known hosts of *C. capitata* (see Liquido et al. 1991). For a first replicate (late March to early May 1992), these included primarily species of *Citrus*; for a second (May to June 1992), approximately half the traps were in stone fruits (*Prunus* spp.) with most of the remainder in *Citrus*. In both replicates, ≈10% of the traps were placed in other hosts (e.g., *Eriobotrya,* loquat; *Psidium,* guava) or in ornamentals. Each trap site contained a Jackson trap, and, at half of the sites, a glass McPhail trap was placed within 2–3 m of the Jackson trap. Each Jackson trap contained a polymer plug (1.5-cm diameter by 2-cm height) impregnated with 2 g of trimedlure (Agrisense, Fresno, CA). McPhail traps were primarily for detecting *Anastrepha ludens* (Loew) and contained a yeast-based bait.

Flies (3–4 d old) were released at four points (46, 137, 228, and 320 m [50, 150, 250, and 350 yards]) around each trap site. The sites and release positions were mapped, and, on two occasions, an individual trap site had to be moved so that releases around one Jackson trap were always >320 m from neighboring trap sites. Aside from the constraint of distance, direction from a release point to the nearest trap was selected arbitrarily and varied throughout the plot. Flies for release at each distance were marked with a distinct color. For release, flies were aspirated into plastic tubes (4-cm diameter by ≈10 cm height; <200 flies per tube) and were taken to the test area. The first replicate was made with releases of 24.7 flies per hectare (10 flies per acre), and the second was with 12.4 flies per hectare. The number of flies released at each point was adjusted so that the overall release density was maintained within each of the four following distance zones: 1–91 (46 m release), 91–183, 183–274, and >274 m. Sex ratios of released flies were not determined but were assumed to be 1:1. After each release, traps were checked weekly for 5 wk. Trap sites were not

moved during that period. Any flies captured were identified by entomologists from the California Department of Food and Agriculture (CDFA) and from Orange County as part of their routine duties.

For analysis, the overall proportion of flies recaptured from each distance was computed for each 2.6-km^2 block. The proportions were subjected to analysis of variance (ANOVA) following arcsine-square root transformation. Means were separated using Fisher's least significant difference test (Wilkinson 1990).

High-Density Trapping. We also used release–recapture to evaluate a supplemental delimitation system of 1,000 panel traps per 2.6 km^2. This system has been placed routinely around sites of recent detections of *C. capitata* in California. The traps were yellow cardboard panels 14 by 23 cm (Seabright Enterprises, Emeryville, CA), coated on both sides with 19 g per trap of 12.5% trimedlure in stickum. For each of two replicates (May and August 1992), we selected two 0.26-km^2 (0.1 square mile) plots within residential sections of Anaheim or Fullerton (Orange County), CA. Allowing for the constraint that traps must be hung in trees, 100 trap sites in each plot were arranged in a grid 10 by 10 cm with ≈51 m between traps. One thousand marked sterile flies were released in 1 d at the center of both plots. Before the releases, traps were hung in only one of the two plots. After 1 wk, those traps were replaced with new traps, and traps were hung at the trap sites in the other plot. The second group of traps was left in place for an additional 3 wk. Orange County and CDFA entomologists identified all flies that were captured.

Probability Models. To estimate the probability of detecting populations of Mediterranean fruit flies, the presence of a male fly within a trapping system was assumed to be a binomial event. Specifically, at a given distance from a trap, a male was assumed to have a probability p of being captured and a probability q ($= 1 - p$) of not being caught. The probability of capturing i males (P_i) from a population containing n males could then be computed directly using binomial expansion (e.g., Steel & Torrie [1960]), where:

$$P_i = \frac{n!}{i!(n-i)!} p^i q^{n-i} \qquad (1)$$

Because a population will be detected any time >0 flies are caught, the sensitivity of detection systems was estimated by computing the probability of capturing no flies ($i = 0$) and subtracting the result from one. Thus, equation *1* was reduced to:

$$P_0 = (1 - p)^n \qquad (2)$$

The proportions of males trapped in release–recapture studies now provide estimates of p. For example, if release–recapture tests indicate that a trapping system typically captures 1% of the males in an area, then the probability of not detecting a population of flies containing 100 males would be $(1-0.01)^{100} = 0.366$. This computation predicts that the system will detect the population within one generation 100% − 37% = 63% of the time. The estimates of p used in our models were obtained by multiplying the proportions of males recovered in release–recapture tests by 0.8 to compensate for possible differences between wild and laboratory-reared flies. In two separate release–recapture studies with trimedlure-baited traps, recovery of adult *C. capitata* collected from the field (as larvae in fruit) was ≈20% lower than that of sterile, laboratory-reared flies (Wong et al. 1982; D.R.L., unpublished data).

Estimates of the probability of detecting a population with the standard detection grid were based on the assumption that all flies in the population originated from a single point source. Probabilities of capturing 0 flies were computed separately for each distance zone (i.e., 0–91, 91–183, 183–274, and >274 m from the trap). The probability for each zone then was weighted for (i.e., multiplied by) the proportion of the total area that fell within that zone (e.g., at 10 traps per 2.59 km^2, each trap covers [1,609 m]^2/10 = 259,000 m^2; of that area, [91 m]$^2 \times \pi$ = 26,016 m^2, or 10%, falls within 91 m of the trap). The weighted probabilities then were summed across distance zones.

For computing probabilities of detection over multiple generations, the overall probability (i.e., across distance zones) of capturing 0 flies within one generation was raised to the power of the number of generations. This procedure was based on the assumption that the location of trap sites was rerandomized once per generation. This differs slightly from the actual practice of moving traps every 6 wk.

Proportions of flies recaptured by Cunningham & Couey (1986) also were used to estimate the sensitivity of the detection and delimitation trapping systems. Those authors released flies in a macadamia orchard at distances of 7.5, 15, 30, 60, 120, and 240 m from individual traps. Based on their recapture data, they developed the predictive equation $Y = 0.6972(0.9782)^x$, where Y is the proportion of males recaptured and x is the distance in meters from the release point to the trap. We used this equation to estimate the probability of detecting point-source populations as described, except that probabilities and proportions of total area were computed individually for successive 1-m intervals. Data from additional release–recapture studies (e.g., Wong et al. 1982, Plant & Cunningham 1991) were not appropriate for this type of probability analysis because of the design of the plots.

Table 1. Marked *Ceratitis capitata* captured when released at different distances from Jackson traps baited with trimedlure within four blocks (1.6 by 1.6 km) in Santa Ana, CA

Distance from traps, m	First release		Second release		Mean % of flies captured ± SEM
	Flies released per block	Mean no. flies captured ± SEM	Flies released per block	Mean no. flies captured ± SEM	
46	650	20.0 ± 1.9	330	9.3 ± 2.3	2.94 ± 0.35c
137	1,950	11.5 ± 3.9	970	6.5 ± 1.5	0.63 ± 0.12b
228	2,860	4.8 ± 1.5	1,430	2.0 ± 0.9	0.15 ± 0.04a
320	940	1.0 ± 0.4	470	1.0 ± 0.4	0.16 ± 0.05a

Means followed by the same letter are not significantly different ($P = 0.01$; Fisher's LSD test). Actual means are shown, but arcsine of square roots of proportions were used for ANOVA.

Results

Detection Trapping. Overall, 149 of 25,600 flies (0.58%) were recovered from the first release, and 76 of 12,800 (0.59%) were recovered from the second. Only four of the 225 flies were captured in McPhail traps. Sex of captured flies was determined for the second (but not the first) release, and only two were females. In analyses of the proportions of flies recaptured, effects of replicate ($F = 0.001$; df = 1, 9; $P = 0.97$) and two-way interactions ($P \geq 0.10$) were not significant ($\alpha = 0.05$) and were pooled into the error term. The proportion of *C. capitata* recaptured decreased significantly as distance from the trap increased up to 228 m ($F = 73.0$; df = 3, 25; $P < 0.001$), but recapture rates for flies released at 228 and 320 m were similar (Table 1). In total, the effect of distance accounted for 87% of the experimental sums of squares. Effects of block on mean percentage recapture were also significant (range = 0.43 to 0.63%; $F = 3.27$; df = 3, 25; $P = 0.04$).

High-Density Trapping. In plots that were trapped continuously, yellow panels captured 223 (May) and 271 (August) of the 1,000 marked flies during the 4-wk periods. Of those, 20 (May, 9%) and 9 (3%) were captured after the end of the 1st wk. In plots that were not trapped during the 1st wk, only 78 (May) and 19 flies were captured, indicating that the majority of the flies either dispersed from the plot or died during the 1st wk. Thus, although panels in both of the continuously trapped plots caught approximately half of total males, they caught higher percentages of the males that were actually alive and present in the plots.

Probability Models. Computations based on the release–recapture data predict that, within one generation, a grid of 3.9 trap sites per square kilometer will detect 50% of populations containing ≈200 male *C. capitata* and essentially all populations of >3,000 males (Fig. 1). The assumption that all flies arise from a single point in space produces more conservative estimates of detection capabilities than the alternate assumption that flies are distributed evenly throughout an area (Fig. 1). For the latter, computations were based on a single, overall value for proportion of flies recaptured.

The predicted probability of detecting a population increases substantially over the course of several generations (Fig. 2). For example, if a population remains stable throughout five generations (≤1 yr), the detection grid would be expected to capture at least one male from 50% of populations that contain ≈20 males per generation and from nearly all populations of >300 males per generation. The equation of Cunningham & Couey (1986) predicted that recapture rates would be substantially higher than those we observed for males that were close to traps but would be lower for males that were over ≈200 m from a trap. As a result, probabilities of detection based on Cunningham & Couey's equation were somewhat higher than ours for populations of under ≈400 males, but their data indicated a greater risk of missing relatively large populations that were located long distances from traps (Fig. 2).

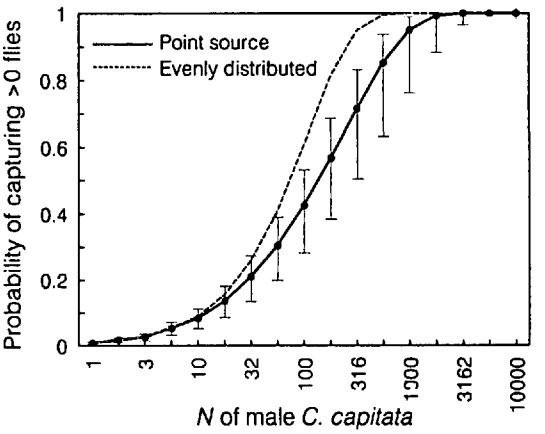

Fig. 1. Estimated probabilities of capturing one or more male *Ceratitis capitata* in an array of 10 trimedlure-baited traps per 2.6 km^2 when all flies either arise from a single point in space or are distributed evenly throughout the habitat. Error bars indicate probabilities computed with recapture rates that are ±1 95% CI from the mean.

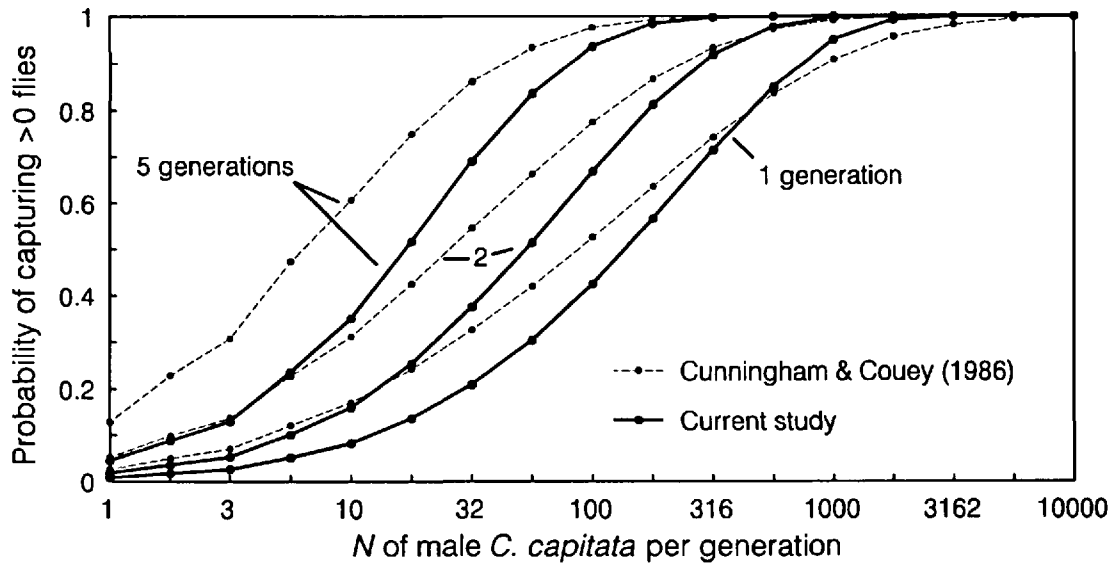

Fig. 2. Estimated probabilities of capturing one or more male *Ceratitis capitata* in an array of 10 trimedlure-baited traps per 2.6 km^2 over the course of 1, 2, or 5 generations. Trap sites were assumed to be relocated following each generation.

A system of 1,000 panel traps per 2.6 km^2 appears to be a sensitive tool for detecting populations of *C. capitata*. Our model predicts that at least one of two males will be caught >50% of the time, and one or more flies almost always will be captured from populations with >10 males (Fig. 3). Predictions based on the single value of p from our release–recapture tests are similar to those based on the equation of Cunningham & Couey (1986).

Discussion

Simple probability models appear to have great potential but have been used little in the design and evaluation of systems for detecting exotic insects. An exception is Calkins et al. (1984), who estimated the probabilities of detecting *Anastrepha suspensa* (Loew) with McPhail traps. They measured the proportions of *A. suspensa* recaptured at four release densities and calculated the probabilities (P) that one or more of n traps would catch >0 flies. This procedure may be appropriate for situations in which few traps are used in limited areas (e.g., individual orchards) but is inappropriate for large-scale detection operations such as the *C. capitata* trapping program in California. Because P is computed from the proportion of traps that catches flies, the resulting estimates are influenced by such factors as the distribution of flies among traps (more contagious distributions yield lower values of P) and ratios of total released flies to total traps. The alternate approach (i.e., using the proportion of n flies recaptured) may be more accurate and less complex. Nonetheless, the results of Calkins et al. (1984) clearly suggested that probability models would be useful to managers who had to decide on the density of traps needed to meet program goals.

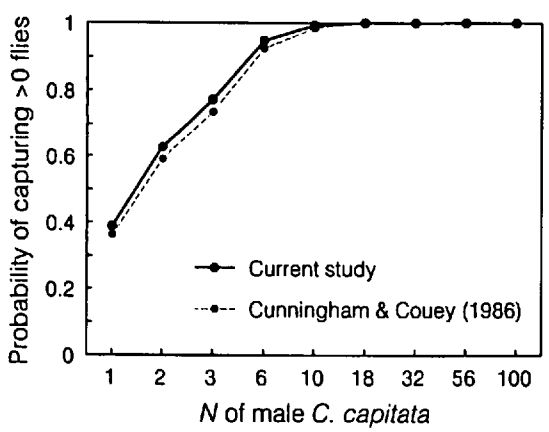

Fig. 3. Estimated probabilities of capturing one or more male *Ceratitis capitata* in an array of 1000 trimedlure-baited yellow sticky panels per 2.6 km^2.

Recovery of flies in our assays of the detection system was in agreement with data from the 1991–1992 Mediterranean fruit fly eradication program. Over 8 mo, nearly 1.4 billion sterile *C. capitata* were released, primarily from aircraft, into a 86-km^2 zone in a residential area within Los Angeles. In the release area, Steiner traps were deployed at five per 2.6 km^2 and recovered 0.205% of the released flies (i.e., individual traps captured a mean of ≈0.04% of the flies released into the surrounding 2.6-km^2 area). In our study, the mean proportion of flies captured in individ-

ual detection traps was slightly higher (0.06% per trap), but Jackson traps are somewhat more efficient than Steiner traps (Harris et al. 1971).

Cunningham & Couey (1986) predicted that recapture rates should have been several times higher than those observed in southern California. Their data indicated that 2.2% of flies would be recovered using 10 traps per 2.6 km^2 (we observed 0.6%), and 1.1% would be trapped at five traps per 2.6 km^2 (0.2% were recovered in the eradication program). Cunningham & Couey (1986) based their predictions on data developed in an orchard of *Macadamia* sp. Appetitive movement of the flies was probably greater in a habitat containing parallel rows of uniformly sized trees and no larval hosts (see Liquido et al. [1991]) than in urban and suburban settings with more random arrangements of host plants, nonhost species, and buildings. Weather also influences the efficiency of detection trapping systems. For example, the proportion of flies captured in trimedlure-baited traps during sterile insect release programs tends to decline during periods of cool, wet weather (based on figures from the Los Angeles Area Daily Report, Cooperative Medfly Project). Ideally, models to estimate the probability of detecting *C. capitata* would include effects of environmental factors on proportions of insects trapped. Additional factors that potentially could limit the applicability of our results include geographic variation in responsiveness of males to trimedlure (our results were based solely on Hawaiian strains) and possible abnormal behavior of flies immediately after release (see Baker & Chan [1991]).

Despite these potential limitations, we believe that our results provide accurate estimates of the sensitivities of current detection and delimitation trapping systems. Recapture rates were consistent and in agreement with data from sterile-insect release programs. Predictions of the sensitivity of the detection system were relatively similar when based either on our data or on the predictive equation of Cunningham & Couey (1986). We took a conservative approach by assuming that all flies arose from a single point in space and by adding a correction factor for possible differences between wild and laboratory-reared flies. In addition, our model assumes that, for a given distance from a trap, all males have an equal probability of being captured. In the field, any fly-to-fly variation in the probability of being captured would reduce the actual probability of capturing 0 flies and thus increase the probability of detecting a population.

These findings indicate that 10 rotating trap sites per 2.6 km^2 are adequate for detecting local populations of *C. capitata* when they are small enough to be eradicated using the sterile-insect technique. At least one fly will be captured from most populations of several hundred adults and from essentially all populations that reach a size of a few thousand flies. At these detection levels, predicted ratios of sterile to wild flies agree with the values of thousands to one that have typically been observed at the start of California's sterile-release programs (Los Angeles Area Daily Report, Cooperative Medfly Program). Further, an array of 1,000 panel traps per 2.6 km^2 almost always will detect even a very few flies and is an effective tool for delimiting populations and confirming eradication. In this context, the current trapping systems are appropriate for detecting and delimiting introduced populations of *C. capitata* in southern California.

Regardless, recent increases in detections of *C. capitata* have raised concerns about the functional effectiveness of California's trapping systems. In 1989 (Carey 1991a), 1992, and 1993 (Los Angeles Area Daily Report, Cooperative Medfly Program), detections of single infestations were followed by fly finds at additional foci. In 1993 alone, 400 wild flies were captured across 33 locations and four counties in the Los Angeles area. Assuming that the flies at all or most of these locations came from separate introductions, our results, along with program experience, indicate that the detection system is adequate. USDA–APHIS has intercepted *C. capitata* destined for California in passenger baggage and other sources of fruit smuggled for private consumption on hundreds of occasions since 1970 (Miller 1992), but the actual frequency of such introductions may not be sufficient to account for recent levels of infestation. The number of introductions resulting from other sources (e.g., commercial fruit-smuggling operations) is unknown.

An alternative assumption is that most infestations in California are founded by flies that originate in California. Mated female *C. capitata* around Los Angeles potentially could emigrate and start new infestations before populations at their original sites are detected and eradicated. The extent of such occurrences in southern California is difficult to estimate because little is known about *C. capitata* in terms of migratory activity, the potential for human transportation of various life-stages within southern California, or the population biology of early portions of the colonization process (Carey 1991a). Carey (1991a, b) extended this assumption and proposed that a population of *C. capitata* has been established continuously in southern California since 1975 and has spread throughout the Los Angeles basin. With the latter hypothesis, the single infestation that was detected in 1991, for example, actually would have been only one of many subpopulations that were distributed across several counties (Carey 1991a, b). Our findings suggest that a total of as few as 1,000 males outside of the known infestation would have resulted in the detection of additional sub-

populations during ≈9 of every 10 generations (Fig. 2). Over the course of five generations (at most, a year), a total population of as few as 100 males per generation would have produced approximately a 90% chance of finding additional flies. The lack of additional detections in 1991 suggests that there may have been too few flies to spread among the numerous viable subpopulations that Carey assumed to be present. Thus, although a system of 10 trap sites per 2.6 km^2 is possibly not sensitive enough to detect the majority of introduced populations of *C. capitata* before they spread to additional sites, any broad-based, established population almost certainly would result in numerous widespread detections throughout the year. Historically, this has not been the case (Carey 1991a).

In summary, the trapping system we tested for *C. capitata* in California will detect local infestations while they are small enough to be eradicated using available technology. Further conclusions regarding the effectiveness of this system require additional biological and regulatory information.

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