CSIRO PUBLISHING
www.publish.csiro.au/journals/ajea *Australian Journal of Experimental Agriculture*, 2005, **45**, 1335–1340

Zero catch criteria for declaring eradication of tephritid fruit flies: the probabilities

A. Meats[A,B] *and A. D. Clift*[A]

[A]Fruit Fly Research Centre, School of Biological Sciences A08, University of Sydney, NSW 2006, Australia.
[B]Corresponding author. Email: awm@bio.usyd.edu.au

Abstract. We examine procedures for declaring an area free of pest fruit flies following an eradication campaign. To date, the acceptable period of trapping zero flies has been calculated without an estimate of the probability of being wrong. The zero trapping periods are usually shorter when declaring local 'area freedom' from an endemic fly, than when claiming eradication of an exotic species. We use a model to calculate the probability of zero trap captures and therefore the probability of trapping further flies. The latter probability is always finite. A zero trapping result does not indicate the absence of flies. There must also be evidence of what constitutes a non-viable density, as indicated by the trapping rate. The non-viable densities of certain pest fruit fly species are known from decades of managing small incursions in fly-free zones. There is no need for implementation of eradication procedures if the trapping rate is sufficiently low, in these areas. For a given density of flies (defined in terms of expected mean catch per trap per week), the probability of zero trap captures reduces with time and the number of traps employed. If the model calculations use a non-sustainable density (inferred from trapping rate) then we may declare the actual density of flies to be less if the trapping result is zero for a given number of weeks with a given number of traps when the model predicts the probability of such a result to be sufficiently low, according to a criterion that is selected at a level suited to the purpose of the declaration.

Additional keywords: invasions, incursions, Allee effect, extinction.

Introduction

Eradication criteria

Many tephritid fruit fly infestations around the world have been eradicated by annihilating males of species that respond to methyl eugenol (Steiner *et al*. 1970; Koyama *et al*. 1984; Hancock *et al*. 2000; Seewooruthun *et al*. 2000) or by releasing sterile insects (Iwahashi 1977; Fisher *et al*. 1985; Schwarz *et al*. 1989; Sproul *et al*. 1992; Gabayet *et al*. 1996; Kuba *et al*. 1996). These campaigns were used against the Oriental fruit fly, *Bactrocera dorsalis* (Hendel); the Asian Papaya fruit fly, *B. papayae* (Drew and Hancock); the Queensland fruit fly, *B. tryoni* (Froggatt); the Melon fly, *B. cucurbitae* (Coquillett); and the Mediterranean fruit fly (Medfly), *Ceratitis capitata* (Wiedemann). The most well known example that involved another pest species, was the eradication of the screwworm fly, *Cochliomyia hominivorax* (Coquerel) from North America and most of Central America using sterile insect release (Krafsur 1998).

Tephritid fruit fly eradication is monitored by an array of traps containing a male lure and sometimes also by fruit sampling (e.g. Kuba *et al*. 1996). Declaring eradication of flies occurs after a fly-free period. The period lengths have varied, appear arbitrary and there have been no calculations of the probability of being wrong (Table 1). Sometimes, no criterion for declaring eradication in terms of fly-free weeks has been given (e.g. Schwarz *et al*. 1989).

In countries such as the USA and Australia, eradication of spot pest infestations, such as Medfly, is common to regions normally claiming area freedom (fruit fly exclusion zones). Such eradications are routine and not reported in the literature. Official government codes of practice for such procedures are unpublished and details differ according to both the country and pests involved. Meats *et al*. (2003) reviewed the Australian codes of practice for Medfly and Queensland fruit fly. They examined 25 years of data from spot eradications of each species and calculated the radii of the infested areas. In Australia (and presumably elsewhere) the criteria for re-instatement of local area freedom vary according to the intended market. The fly-free period required has varied from 12 weeks or the potential length of 1 generation plus 28 days (whichever is the longer), to the potential length of 3 generations plus 28 days. In the case of the Queensland fruit fly, the latter period would be about a year in the southern fruit growing regions of the Australian mainland, and as little as 16 weeks in tropical regions (Meats 1989). In all cases where area freedom was restored, development models were used to calculate the relevant period with a high degree of precision (e.g. Fisher *et al.*

 10.1071/EA04108 0816-1089/05/101335

1985) yet no rationale is given in terms of probabilities of being wrong.

The meaning of zero catch rates

To estimate the total numbers of an organism in a given area, the sampling method must be either precise, as in the case of quadrat sampling, when all or an estimated proportion of the organisms are seen or found in each quadrat sampled (Caughley and Sinclair 1994); or it must be calibrated with the release of known numbers of marked organisms of the type being sampled. Fletcher (1974) was able to do the latter for the Queensland fruit fly, *B. tryoni*, and estimated an array of traps spaced at 400 m, trapped about 1% of mature males present per day in the warmer months of the year. However, the problem remains as to how to interpret a zero catch rate. Aside from the fact that flies may not respond to traps in cold weather (Fletcher 1974) it would be possible for populations to be so sparse that, even in favourable seasons, several weeks may elapse without trapping anything.

One approach calculates the probability of zero catch for a given number of zero trapping weeks, with a given number of traps, when there is a mean expectation (in terms of catch per trap per week) that some flies should be caught (Clift and Meats 1997, 2004). However, the results are not easy to interpret unless one knows the significance of low catch values per trap per week. Fortunately, decades of experience with low density populations of Medfly and the Queensland fruit fly (incursions into a fly-free zone) has established the significance of certain low trapping rates. This knowledge has been incorporated into the codes of practice (Meats *et al*. 2003). The latter paper examined the records of incursions in trap arrays with 400 m spacing in South Australia between 1976 and 2000. The codes of practice, for the management of incursions of these species into zones having area freedom, call for no counter measures (insecticidal treatment or release of sterile insects) if the trapping rate is very low within a 1 km radius (which would usually involve a group of 20 traps). Thus for the Queensland fruit fly, no counter measures are taken if 4 or fewer males are detected within a 1 km radius in a 2 week period. For Medfly, the limit is 2 male flies trapped within a 1 km radius in 2 weeks. Meats *et al*. (2003) found that these cases (where there were no further detections) comprised 71% and 18% of incursions of Queensland fruit fly and Medfly, respectively. Those proportions of incursions were not of a viable density [presumably due to some aspect of the 'Allee effect' such as a lowered chance of finding mates (Meats 1998; Meats *et al*. 2003)]. In all other cases, local area freedom was suspended and insecticidal spraying or the release of sterile flies ensued but it is possible that some of these incursions would also have died out of their own accord. Nevertheless, we can define non-viable densities in terms of the acceptable trapping rates, and for such densities (and ones much lower if a safety margin is required), we can calculate the probability of trapping zero flies in a given period.

Previous attempts have used the output results of a series of 1000 iterations of a computer model. This model simulated a sequence of trap catches for a number of consecutive weeks with the probability of catching a fly each week varying from the mean expectation according to a given frequency distribution (Clift and Meats 1997, 2004). This proved cumbersome when we wished to extend the investigation to a greater number of weeks and densities. Because the aggregate result of the iterations converged on the corresponding mean expectation, the present paper takes the simpler approach of using mean expectations derived from the zero term of the Poisson equation. We did not use other distributions such as a negative binomial series because their predictions tend to converge with those of the Poisson for very low densities, when most traps catch nothing in a given week (Clift and Meats 1998).

Methods

Calculations

To establish the mean expectation of the number of flies (m) caught with time in a trap array of given size, the following equation was used:

$$m = c_{tw}\, t\, w \qquad (1)$$

where c_{tw} is the catch per trap per week, t is the number of traps and w is the number of weeks.

Alternatively, m can be calculated by summing all the non-zero term predictions of the Poisson equation.

To find the probability (P_0) of a zero catch with time on a given array, the zero term of the Poisson equation was used:

$$P_0 = \exp(-m) \qquad (2)$$

Table 1. Fly-free periods used for declaration of eradication

Reference	Place	Species	Fly-free criterion (weeks)
Steiner *et al*. (1970)	Mariana islands	*B. dorsalis*	18
Ushio *et al*. (1982)	Amami island (Japan)	*B. dorsalis*	27
Koyama *et al*. (1984)	Okinawa island (Japan)	*B. dorsalis*	52
Kuba *et al*. (1996)	Okinawa island (Japan)	*B. cucurbitae*	50
Sproul *et al*. (1992)	Perth (Western Australia)	*B. tryoni*	52
Hancock *et al*. (2000)	North Queensland (Australia)	*B. papayae*	104
Seewooruthun *et al*. (2000)	Mauritius	*B. dorsalis*	104

To calculate the number of zero catch weeks required to achieve a critical value of P_0 (such as 0.01, 0.001 or 0.00003) with a given value of c_{tw} was found by:

$$w = (-\ln P_{0\ crit}) / (c_{tw}\ t) \tag{3}$$

Choice of array sizes (number of traps) and trapping rates

The array size (number of traps, t) most pertinent to the codes of practice, for management of breaches of area freedom, is 20. This is the number of traps within a 1 km radius (when spaced at 0.4 km). In an area-wide campaign of eradication, there is a reduction of pests to remnant patches or foci of about 2 km radius. These are then eradicated individually (Koyama *et al*. 1984; Meats 1998; Clift *et al*. 1998; Clift and Meats 2004). Thus, the largest effective array size for declaring eradication would be about 100 traps. This would cover an area 4 by 4 km or 2.26 km radius. If a larger array was selected then the outlying traps would be irrelevant to the remaining infestation and, if included in the calculations, the estimate would have an unacceptably low probability of zero.

The trapping rates chosen should signify a known unviable density or represent the rate observed immediately before the sequence of zero catches. In the case of spot infestations, the codes of practice for both the Queensland fruit fly and Medfly consider 1 fly per 2 weeks within 1 km to be unviable (Meats *et al.* 2003). Such a rate is equivalent to 0.025 flies per trap per week if the traps are spaced 0.4 km apart (20 traps within a 1 km radius). In the case of an exotic incursion, we could use a safety margin and a lower rate, perhaps more appropriate to larger areas, of 0.001 flies per trap per week.

A potential problem in using this method is that the codes of practice stipulate the local augmentation of the trap arrays, for periods when trapping rates exceed a specified threshold. Thus, the number of traps in an array would not be constant. Another is the uneven distribution of flies. However, there is no need for a method to deal with either potential problem because the continued use of a relevant number of permanent traps for t is valid, as discussed later.

Results

Table 2 shows the expected number of flies caught *v*. time for arrays of 2 different sizes, 20 and 100 traps, and 2 different trapping rates, 0.025 and 0.001 flies per trap per week. The number expected increases with time, size of trap array and the underlying mean catch per trap per week. There is a high number expected for extended trapping periods, even at a low catch rate. Thus, a zero catch over time may mean that the density is low or possibly zero. Obtaining a more precise diagnosis can be achieved by calculating the probability of getting a zero result over time. Table 3 shows the probabilities declined to very low levels over time, enabling us to deduce whether a zero result was statistically significant, according to the critical probability of such a result (such as $P_{0\ crit}$ = 0.01, 0.001, 0.00003).

Table 4 shows the number of weeks of zero trapping required to achieve these critical probabilities, when the mean trapping rate c_{tw} is actually finite.

Discussion

Choosing appropriate risk levels

For a given density of flies (defined in terms expected mean catch per trap per week) the probability of zero reduces over time and the number of traps employed. If we choose for our model a density accepted as non-viable, then the actual density declared may be less than this if a zero result is achieved when the model predicts the probability of such a result to be sufficiently low according to a criterion ($P_{0\ crit}$) that is selected at a level suited to the purpose of the declaration. The method is versatile because it is possible to select a relevant non-viable density (in terms of a trapping rate, c_{tw}) and adjust the number of traps (t) and/or the number of weeks (w) to give the desired value of P_0, (equation 2). Alternatively, adjustments could be made to the number of traps to give a desired number of weeks necessary to achieve a desired $P_{0\ crit}$ (equation 3).

This versatility is useful because the relevant values of t, c_{tw} and $P_{0\ crit}$ may differ according to the situation. For instance, we suggested earlier that in cases of local area freedom for either the Queensland fruit fly or Medfly, the

Table 2. Mean expectation of total catch over time at different fly densities by arrays of 20 or 100 traps

Densities related to given mean catch per trap per week (mean trap catch)

Number of weeks	Mean trap catch 0.025[A] 20 traps[B]	100 traps[C]	Mean trap catch 0.001 20 traps[B]	100 traps[C]
8	4	20	0.16	0.8
12	6	30	0.24	1.2
16	8	40	0.32	1.6
26	13	65	0.52	2.6
32	16	80	0.64	3.2
52	26	130	1.04	5.2
78	39	195	1.56	7.8
104	52	260	2.08	10.4

[A]Equivalent to trapping 1 fly per 2 weeks within 1 km radius (20 traps).
[B]Equivalent to an area of 1 km radius.
[C]Equivalent to an area 4 by 4 km; expectations for arrays of other sizes will be *pro rata* for a given time and for other times at a given trap array.

Table 3. Probability of catching zero flies over time at different fly densities by arrays of 20 or 100 traps

Densities related to given mean catch per trap per week (mean trap catch)

Number of weeks	Mean trap catch 0.025[A] 20 traps[B]	100 traps[C]	Mean trap catch 0.001 20 traps[B]	100 traps[C]
8	0.018	2×10^{-9}	0.85	0.45
12	0.002	9×10^{-14}	0.79	0.30
16	0.0003	4×10^{-18}	0.73	0.20
26	2×10^{-6}	6×10^{-29}	0.59	0.07
32	1×10^{-7}	2×10^{-35}	0.53	0.04
52	5×10^{-12}	3×10^{-57}	0.35	0.006
78	1×10^{-17}	2×10^{-85}	0.21	4×10^{-4}
104	3×10^{-23}	1×10^{-113}	0.12	3×10^{-5}

[A]Equivalent to trapping 1 fly per 2 weeks within 1 km radius (20 traps).
[B]Equivalent to an area of 1 km radius.
[C]Equivalent to an area 4 by 4 km; expectations for arrays of other sizes will be *pro rata* for a given time and for other times at a given trap array.

most relevant values of c_{tw} and t would be 0.025 and 20, respectively, because the radii of infestation are almost always under 1 km. Values of 0.001 and 100 may be appropriate in the case of eradication of a remnant population of an exotic species from an area of about 2 km radius. The desired value of $P_{0\ crit}$ may also differ according to requirements. For eradication of an exotic species, only a very low level such as 0.00003 (probit 9) may be acceptable, but values of 0.001 or 0.0001 may suffice for local area freedom because a higher risk of an incorrect result is more acceptable for a small area. Thus for local area freedom for the Queensland fruit fly we may choose t, c_{tw} and $P_{0\ crit}$ as 20, 0.025 and 0.001, respectively so that we could make our eradication declaration at 14 weeks (Table 4). For an exotic incursion more conservative values of 100, 0.001 and 0.00003 would be used and declare eradication at 104 weeks (as indicated in Table 4).

According to the present codes of practice, the highest trapping rate within a 1 km radius that requires no counter measure (insecticide application or release of sterile insects) is 2 per fortnight for Medfly (c_{tw} = 0.05) and 4 per fortnight for *B. tryoni* (c_{tw} = 0.1). The shortest fly-free period required to re-instate area freedom is 12 weeks or the potential length of 1 generation, plus 28 days, whichever is the longer. The period before re-instatement also depends upon temperature. For Medfly and *B. tryoni*, the number of weeks for P_0 to drop to 0.00003 with those values of c_{tw} is 10.4 and 5.2, respectively, thus a 12-week fly free period is well in excess of the probit 9 criterion for each species. However, it must be borne in mind that the latter times are the consequence of assuming a relatively high value for c_{tw} (which is the catch per trap equivalent to the highest non-sustainable density). Such a value is acceptable for local area freedom but may not be acceptable for the purposes of declaring extinction of an exotic pest. It would be prudent to assume that the value may be lower because the risks of being wrong are much greater, and apply to a whole country or large geographical area rather than a small local radius of a few km.

Assumptions about dispersion of catches in space and time

The results of equations 2 and 3 are very sensitive to c_{tw} as can be seen from the values in Tables 3 and 4, respectively. The c_{tw} value pertains to catch per trap per week for a given array and is an index of density. For either equation, the average of outputs using 2 different values of c_{tw} can be widely different from the output using the average value of c_{tw}. Thus we must address the possibility that our method has limited value because it uses c_{tw} to indicate the average density within the given trap array and that average is constant over time. Under the current codes of practice, the values of catch per trap per week pertain to a block of 20 traps, thus it does not matter as far as the codes are concerned whether flies are caught by 1 trap, or more. In reality, only 1–2 flies are trapped in any week and only for a week or 2, so the distribution of flies is difficult to ascertain.

The null hypothesis is our assumption that flies are constantly at a certain density x with time where x determines the mean trapping rate m as defined in equation 1. This is useful for those long periods with zero catches when equation 2 predicts that there is only a minimal chance of obtaining zero flies when in fact we actually trapped zero flies. Thus we can quote the odds that the density is less than the one assumed by the null.

Relevant trap spacing

The method requires that traps be spaced sufficiently close to intercept at least some flies from a small incipient or remnant population. For the Queensland fruit fly, 0.4 km between traps is adequate, but 1 km is unsatisfactory (Meats 1998*a*). Medfly has much less tendency to disperse (Wong *et al.* 1982; Cunningham and Couey 1986; Plant and Cunningham 1991) so a 0.4 km array of traps is barely adequate and at greater spacing, 'cryptic' populations may persist undetected for several generations (Cunningham and Couey 1986; Carey 1996). Thus for this species, the practice of using supplementary traps once a fly is detected is necessary in order to locate the epicentre of an incursion (Meats *et al.* 2003). In the case of eradicating the Asian Papaya fruit fly from north Queensland, the trap array spacing was >0.4 km; the average at Mareeba was 0.8 km with a range from 0.4 km to >1 km, depending partly upon the difficulties presented by the terrain (Meats 1998*b*). Trapping of flies occasionally between long intervals of zero trapping may suggest that the local population is persisting at a low level. However, there was a different reason for this phenomenon, in the case of the campaign against the Asian Papaya fruit fly in north Queensland. In this case, the phenomenon was due to a few remnant populations of considerable size persisting at relatively long distances from

Table 4. Number of weeks to critical values of P_0 at 3 mean trapping rates c_{tw} (catch per trap per week)

P_0	c_{tw} = 0.025		c_{tw} = 0.01		c_{tw} = 0.001	
	20 traps	100 traps	20 traps	100 traps	20 traps	100 traps
0.01	9.2	1.84	23	4.6	230	46
0.001	13.8	2.8	34.5	6.9	345	69
0.00003	21	4.2	52	10.4	521	104

any trap (Hancock *et al*. 2000). This is consistent with the finding of Meats (1998*a*) that if trap spacing is too large, some flies from an incipient or remnant population emerging about midway between traps, may only disperse in very small numbers to the vicinity of a trap even when that population is large. Such a population could be termed 'almost cryptic' or 'semi-cryptic'.

Counting data from supplementary traps

Under the present codes of practice, supplementary traps are set around a permanent trap within a 1 km radius, when the catch rate equals or exceeds a specified number. For *B. tryoni*, this is 2 flies per 2 weeks (c_{tw} = 0.05) and for Medfly in South Australia, supplementary traps are set even when a single fly is trapped. Withdrawal of supplementary traps occurs after 9 weeks if no further flies are caught or 8 weeks after the last fly if counter measures have to be taken (insecticide application or release of sterile males).

The question arises as to whether we should include the supplementary traps in t when using our formulae and if so, as to how we should deal with the problem of the value of t increasing as supplementary traps are set and then declining when they are removed. Both problems are actually irrelevant because we are calculating either: (i) chance P_0 of trapping zero flies in a given radius or area, as shown in Table 3; or (ii) number of zero trapping weeks that would be consistent with a given probability (e.g. P_0 = 0.00003) as shown in Table 4.

For either task, if we increase the array by adding supplementary traps, then to get the same chance (or the number of weeks pertinent to that chance) we have to reduce the value of c_{tw} proportionately. This has the same effect as not counting the supplementary traps in the value of t. In fact, the codes do the same thing. For example, they use the data on flies trapped in a 1 km radius in 2 weeks regardless of whether supplementary traps are present or absent. Thus, the codes imply a lower c_{tw} standard when supplementary traps are set. However, both c_{tw} values indicate the same density, because the supplemented array has proportionately more traps and is therefore proportionately more efficient per unit area.

Discounting winter months

The method assumes that flies are equally trappable at all times. This is also the case with the criteria used by the current codes of practice when declaring loss of area freedom. To calculate the fly-free period for re-instatement of area freedom, the codes use a physiological time scale in terms of 'degree days' (usually equivalent to the time that would be taken at the prevailing temperatures for 1 or 3 generations to elapse, plus 28 days). This protocol allows for development rate variations with temperature that may even be zero in mid winter (Fletcher 1975). The method that we propose uses real time only, based on trapping probabilities, and does not require the calculation of generation length. If temperature influenced the probability of trapping a fly, in a given week, then the codes of practice for outbreak declarations should be altered. In addition, adjustments should be made to the number of weeks predicted for a given probability of a zero trap rate, according to a physiological time scale similar to the one used for generation times. There has been no calibration of trap efficiency at different temperatures, although flies do not respond to traps in winter when cold conditions prevent full maturation of adults (Fletcher 1975; Meats and Khoo 1976). Thus, in view of the relationship of developmental rate to fluctuating temperature given by Meats and Khoo (1976) we suggest weeks in winter are not counted towards the qualifying period of zero trapping, if the mean maximum daily temperature is below 20°C.

References

Carey JR (1996) The incipient Mediterranean fruit fly population in California: implications for invasion biology. *Ecology* **77**, 1690–1697.

Caughley G, Sinclair ARE (1994) 'Wildlife ecology and management.' (Blackwell: Oxford)

Clift AD, Meats A (1997) Using the negative binomial distribution and risk management software to simulate *Bactrocera papayae* Drew and Hancock (Diptera: Tephritidae) metapopulations in an eradication context. In 'Proceedings of the international congress of modelling and simulation'. (Eds AD McDonald, M McAleer) pp. 792–795. (Modelling and Simulation Society of Australia: Canberra)

Clift AD, Meats A (1998) The relation of 'percentage positive traps' to the negative binomial distribution and to progress in the eradication of *Bactrocera papayae* Drew and Hancock (Diptera: Tephritidae) in northern Queensland. *General and Applied Entomology* **28**, 61–64.

Clift AD, Meats A, Gleeson PJ (1998) A dispersal model for papaya fruit fly. In 'Proceedings of the 6th Australasian applied entomology research conference. Vol. 2'. (Eds MP Zalucki, RAI Drew, GG White) pp. 27–31. (Queensland University Press: Brisbane)

Clift AD, Meats A (2004) When does zero catch in a male lure trap mean no tephritid flies in the area? In 'Proceedings of the 6th international symposium of fruit flies of economic importance'. (Stellenbosch: RSA in press)

Cunningham RT, Couey HM (1986) Mediterranean fruit fly (Diptera: Tephritidae): distance/response curves to trimedlure to measure trapping efficiency. *Environmental Entomology* **15**, 71–74.

Fisher KT, Hill AR, Sproul AN (1985) Eradication of *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae) in Carnarvon, Western Australia. *Journal of the Australian Entomological Society* **24**, 207–208.

Fletcher BS (1974) The ecology of a natural population of the Queensland fruit fly, *Dacus tryoni*. VI. Seasonal changes in fruit fly numbers in the areas surrounding the orchard. *Australian Journal of Zoology* **22**, 353–363. doi:10.1071/ZO9740353

Fletcher BS (1975) Temperature regulated changes in the ovaries of overwintering females of the Queensland fruit fly, *Dacus tryoni*. *Australian Journal of Zoology* **23**, 91–102. doi:10.1071/ZO9750091

Gabayet JAR, Flores JR, Hoeflich WE (1996) The Mexican national fruit fly eradication campaign: largest fruit fly industrial complex in the world. In 'Fruit fly pests'. (Eds BA McPheron, GJ Steck) pp. 561–563. (St Lucie Press: Delray Beach, FL)

Hancock DL, Osborne R, Broughton S, Gleeson PJ (2000) Eradication of *Bactrocera papayae* (Diptera: Tephritidae) by male annihilation and protein baiting in Queensland, Australia. In 'Area-wide control of fruit flies and other insect pests'. (Ed. KH Tan) pp. 381–388. (Penerbit Universiti: Pulau Pinang Sains Malaysia)

Iwahashi O (1977) Eradication of the melon fly, *Dacus cucurbitae*, from Kume Is., Okinawa with the sterile insect release method. *Researches on Population Ecology* **19**, 87–98.

Koyama J, Teruya T, Tanaka K (1984) Eradication of the oriental fruit fly (Diptera: Tephritidae) from the Okinawa Islands by a male annihilation method. *Journal of Economic Entomology* **77**, 468–472.

Krafsur ES (1998) Sterile insect technique for suppressing and eradicating insect population: 55 years and counting. *Journal of Agricultural Entomology* **15**, 303–317.

Kuba H, Kohama T, Kakinohana M, Yamagishi K, Kinjo K, Nakasone K, Nakamoto Y (1996) The successful eradication programs of the Melon Fly in Okinawa. In 'Fruit fly pests'. (Eds BA McPheron, GJ Steck) pp. 543–550. (St Lucie Press: Delray Beach, FL)

Meats A (1989) Bioclimatic potential. In 'Fruit flies: biology, natural enemies and control. Vol. 3B'. (Eds AS Robinson, GHS Hooper) pp. 241–252. (Elsevier World Crop Pest Series: Rotterdam)

Meats A (1998*a*) The power of trapping grids for detecting and estimating the size of invading propagules of the Queensland fruit fly risks of subsequent infestation. *General and Applied Entomology* **28**, 47–55.

Meats A (1998*b*) Cartesian methods of locating spot infestations of the Papaya fruit fly *Bactrocera papayae* Drew and Hancock within the trapping grid at Mareeba, Queensland, Australia. *General and Applied Entomology* **28**, 57–60.

Meats A, Khoo KC (1976) The dynamics of ovarian maturation and oocyte resorption in the Queensland fruit fly (*Dacus tryoni*) in constant and rhythmic temperature regimes. *Physiological Entomology* **1**, 213–221.

Meats A, Clift AD, Perepelicia N (2002) Performance of permanent and supplementary traps for Mediterranean and Queensland fruit flies in South Australia 1975–2001: comparison of male lure and food lure traps. *General and Applied Entomology* **32**, 53–57.

Meats A, Clift AD, Robson MK (2003) Incipient founder populations of Mediterranean and Queensland fruit flies in Australia: the relation of trap catch to infestation radius and models for quarantine radius. *Australian Journal of Experimental Agriculture* **43**, 397–406. doi:10.1071/EA02070

Plant RE, Cunningham RT (1991) Analyses of the dispersal of sterile Mediterranean fruit flies (Diptera: Tephritidae) released from a point source. *Environmental Entomology* **20**, 1493–1503.

Schwarz PAJ, Liedo JP, Hendrichs JP (1989) Current programme in Mexico. In 'Fruit flies: biology, natural enemies and control. Vol. 3B'. (Eds AS Robinson, GHS Hooper) pp. 375–386. (Elsevier World Crop Pest Series: Rotterdam)

Seewooruthun SI, Permalloo S, Sookar P, Soonnoo AR, Price NS, Seewooruthun I (2000) The oriental fruit fly, *Bactrocera dorsalis*, eradicated from Mauritius. In 'Proceedings of the Indian Ocean commission, regional fruit fly symposium'. (Eds NS Price, SI Seewooruthun) pp. 207–210. (Indian Ocean Commission: Quatre Bornes, Mauritius)

Sproul AN, Broughton S, Monzu N (Eds) (1992) 'Queensland fruit fly eradication campaign.' (Report of Department of Agriculture: Perth)

Steiner LF, Hart WG, Harris EJ, Cunningham RT, Ohinata K, Kamakahi DC (1970) Eradication of the oriental fruit fly from the Mariana Islands by the methods of male annihilation and sterile insect release. *Journal of Economic Entomology* **63**, 131–135.

Ushio S, Yoshioka K, Nakasu K, Waki K (1982) Eradication of the oriental fruit fly from Amami Islands by male annihilation (Diptera: Tephritidae). *Japanese Journal of Applied Entomology and Zoology* **26**, 1–9.

Wong TTY, Whitehand LC, Kobayashi RM, Ohinata K, Tanaka N, Harris EJ (1982) Mediterranean fruit fly: dispersal of wild and irradiated and untreated laboratory-reared males. *Environmental Entomology* **11**, 339–343.

Received 28 May 2004, accepted 13 October 2004