Review of the outbreak threshold for Queensland fruit fly (*Bactrocera tryoni* Froggatt)

Bernard C. Dominiak[A], **David Daniels**[B] and **Richard Mapson**[C]
[A] Department of Primary Industry NSW, Locked Bag 21, Orange, New South Wales 2800, Australia and the Department of Biological Sciences, Macquarie University, New South Wales 2109, Australia.
[B] Department of Agriculture, Fisheries and Forestry, PO Box 858, Canberra, ACT 2601, Australia.
[C] Department of Primary Industries Victoria, 621 Burwood Highway, Knoxfield, Victoria 3180, Australia.

Abstract

Fruit flies cause losses in horticultural produce across the world and are a major quarantine concern for most countries. Queensland fruit fly (Qfly) is a native to Australia and is also present in a small number of Pacific Island countries. The detection of Qfly in recognized pest free areas triggers quarantine restrictions from domestic and international markets. In Australia, the detection of five male flies has been taken to indicate an outbreak (i.e. unacceptable risk). Matching the domestic standard, many countries have accepted the 5-fly limit as a quarantine threshold. But some other countries have set the detection of two male flies, or even a single fly, as the threshold for an outbreak. This different standard creates an administrative complexity for exporters and trade regulators.

In this paper, we review the published science covering the impediments to pest establishment. Outbreak data from Victoria and New South Wales during 2007 and 2009 are reviewed in relation to the 2-fly and 5-fly thresholds. Large volumes of fruit have been traded within Australia and internationally based on the 5-fly threshold without incident and there is no evidence that the 2-fly threshold is more appropriate. While Qfly is recognized as being capable of longer distance dispersal than some other fruit fly species, it is also recognized as a poor colonizer. The 5-fly threshold is proposed as the most appropriate threshold for imposition of quarantine restrictions and is recommended as a universal standard for harmonization of quarantine regulations.

Introduction

There are about 4500 species of fruit flies worldwide. In the Pacific area alone, there are 350 species of which at least 25 species are regarded as being of major economic importance (Allwood 2000). The genus *Bactrocera* contains over 400 species, distributed primarily though the Asia-Pacific area including Australia (Drew 1974). Tephritid fruit flies cause direct losses to many fresh fruit and some vegetable industries, resulting in adverse impacts on trade and economies of many countries (Li *et al*. 2010, Stephenson *et al*. 2003). With the increasing globalization of trade (Stanaway *et al*. 2001, Plant Health Australia 2010), fruit flies pose a major quarantine concern that is currently monitored through regional surveillance programs (International Atomic Energy Agency 2003, Stephenson *et al*. 2003, Oliver 2007).

The Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) (Qfly) is a major fruit fly pest of Australian horticulture, attacking most fruit and many vegetable crops (e.g. stone fruit, citrus, coffee, tomato, capsicum, pome fruit) (Bateman 1991, Anon. 1996, Hancock *et al.* 2000). Qfly is an Australian native and is currently only found in Australia and on some Pacific islands (Drew 1989, White and Elson-Harris 1992). Given its pest status within Australia, Qfly is also a significant quarantine concern for many trading partners. Markets trading in commodities that may be subject to Qfly infestation require assurance of reliable monitoring grids, evidence-based outbreak thresholds and appropriate quarantine measures (Bateman 1991, Anon. 1996, Clarke *et al.* 2011).

In the early 1990s, Bateman (1991) reviewed existing domestic trade conditions and recommended a uniform agreement among the Australian states for the management of and trade in Qfly host commodities. In response, the Code of Practice for the Management for Queensland Fruit Fly (Anon. 1996) was published, with particular emphasis on managing the Tri-State Fruit Fly Exclusion Zone (FFEZ) so that fruit could be traded domestically with increased efficiency. The FFEZ production area is managed as a pest free area and is recognized by all Australian states as being free from economic fruit flies. Strict quarantine measures are in place to prevent entry of fruit flies and any incursions invoke a rapid and thorough eradication response. Within the FFEZ, four separate pest free areas have been established to facilitate trade into international markets. These include the Riverina area of New South Wales, the Sunraysia region of Victoria / New South Wales, the Riverland area of South Australia, and the Shepparton Irrigation Region of Victoria. Under some circumstances, Qfly do enter the FFEZ and are detected in monitoring traps (Dominiak *et al.* 2003a, Dominiak and Coombes 2009). Single-fly detections are almost always isolated incursions that do not indicate breeding populations (Meats *et al.* 2003).

For domestic trade (Anon. 1996), an outbreak is declared following one (or more) of three thresholds. These thresholds are the detection of:

(1) five male flies within 1 km within 14 days, or
(2) one mated female, or
(3) one or more larvae in fruit grown in the area.

The quarantine distance around any outbreak is 15 km. This domestic trade agreement (Anon. 1996) was broadly adopted in principle by 19 countries as the basis of international trade. However some key components of this agreement, such as the outbreak threshold, have not been accepted by some importing countries. In 1996, the outbreak threshold varied from 1, 2 and 5 male flies for 1, 14, and 3 countries respectively (Robert McGahy personal communication). The threshold of two male flies and five flies (hereafter referred to as 2-fly and 5-fly thresholds) are the most commonly used quarantine thresholds. The 2-fly threshold is based on detections within 400 m while the 5-fly threshold is based on detections within 1 km. By 2009, with increased international acceptance of the 5-fly threshold, this position had changed with 1, 11 and 9 countries accepting 1, 2 and 5 male flies respectively as outbreak thresholds (David Daniels personal communication). These different outbreak thresholds lack a robust scientific basis and create complex administration procedures for trade regulators. An agreed evidence-based Qfly outbreak threshold would harmonize market requirements and thereby facilitate domestic and international trade (Clarke *et al.* 2011). A universal outbreak threshold would have major implications for trade, quarantine and the minimization of pesticides in the environment as part of eradication programs (cover and bait sprays). There is a geometric expansion of areas requiring disinfestation unnecessarily by each kilometre of quarantine radius for outbreaks triggered by a low threshold (Clarke *et al*. 2011).

The purpose of this paper is to review the data from February 2007 to April 2009 for 2-fly and 5-fly thresholds for fruit fly outbreaks in Victoria and New South

Wales, and to examine the published scientific evidence since 1996 regarding incursions, survival, breeding populations and the resultant outbreak thresholds. This review will focus only on male flies as most outbreaks are triggered by the detection of male flies.

Impediments to pest establishment

Founding propagules

It has been shown that the introduction of fruit flies into pest free areas is most often the result of illegal transportation into and the inappropriate disposal of infested host material within the pest free area (Bateman 1991, Dominiak *et al.* 2000, Dominiak and Coombes 2009). This indicates that relatively small parcels of fruit flies are the source of most Qfly detections. Qfly dispersal from these points of introduction is limited by lifespan and the ability to find food to sustain the effort of longer or frequent short flights, survive adverse weather and avoid predation (Meats and Smallridge 2007, Meats and Edgerton 2008, Gilchrist and Meats 2011, Weldon and Taylor 2011). Immature fruit flies disperse for about two weeks in random directions and do not travel in pairs (Fletcher 1974a). Following the introduction of small numbers of Qfly into fruit fly free areas, the chances of a sexually mature male and female occurring in the same tree or group of trees after many days of dispersal is extremely low (Fletcher 1974a, Bateman 1977, Meats 1998, Weldon 2003, 2007, Weldon and Meats 2010). Following the introduction of propagules of infested fruit into fruit fly free areas, Meats (1998) and Meats *et al*. (2003) proposed that flies disperse into a mate-free void and self extinguish, as it becomes increasingly unlikely that they will participate in mating and will therefore not establish a breeding population.

Nutrition

Nutrition is key for Qfly survival, dispersal, reproduction and establishment of new populations. Wild flies must find sugar, minerals, water and protein from products such as bird faeces, honeydew and fruit juice (Bateman 1972, Drew *et al.* 1984, Dalby-Ball and Meats 2000). In dry environments, these products are difficult to find. The average lifespan of Qfly without food and water is approximately 45 hours (Weldon and Taylor 2010, Dominiak unpublished). Qfly require a balanced diet, as diets with too much or too little protein and carbohydrate result in adverse effects on either longevity or reproduction (Prabhu *et al.* 2008, Fanson *et al.* 2009). Protein feeding by post-teneral Qfly has been consistently reported to enhance sexual performance (Perez-Staples *et al.* 2007, 2008, Prabhu *et al.* 2008). Bacteria on the surfaces of leaves and fruit appear to be a key food source for Qfly (Drew 1987, Drew and Lloyd 1987, Fletcher 1987). However in fruit fly free regions of southern Australia, populations of these bacteria may be infrequent and erratic owing to unfavourable climate (Drew *et al.* 1984, Courtice and Drew 1984). In the absence of these bacteria, Qfly must find protein from alternative ephemeral sources (Perez-Staples *et al.* 2007, Weldon and Taylor 2011) and therefore a large proportion of flies may not reach sexual maturity and contribute to population growth.

Climate in the FFEZ is normally dry and crops require irrigation. The combination of low humidity and starvation are considerably more punitive for Qfly survival than starvation alone (Weldon and Taylor 2010). Desiccation resistance is generally lower for females than males and resistance also declines with age. Therefore, the lack of available food resources in the environment diminishes the chance of survival to maturity and the chance to compete for a mating. In summary, the FFEZ usually presents as a hostile environment and affords very limited resources for the establishment and spread of Qfly.

Dispersal before mating

Qfly actually spend very little time flying. Fletcher (1973, 1989) noted that flies spend most of their time making trivial flights or walking within the tree canopy. In response to higher fruit abundance, both male and female Qfly visit more leaves and hence spend more time in trees containing more fruit (Dalby-Ball and Meats 2000). Flies move around the canopy primarily by walking, and when they do fly, it is usually over distances of less than 50 mm in an upward direction. In laboratory observations, wild Qfly spend only about 0.6% of their time in flight with walking (67.5%), inactivity (18.0%) and grooming (14%) taking up the remainder of their time (Weldon *et al.* 2010). In the field, Ero *et al.* (2011) reported that resting was the most commonly observed behaviour for Qfly while feeding was rarely observed.

The flight activity patterns and short-range dispersal patterns of emerged adults are similar for male and female Qfly (Weldon and Meats 2007, Weldon *et al.* 2010). Clarke and Dominiak (2010) found a high correlation between male and female trap catches and suggested that changes in male distribution also reflect the distribution of female Qfly. Fletcher (1973) reported that the weekly declines of released Qfly were similar for males and females. Meats (1998) also assumed that males and females had similar dispersal. Therefore the trapping of male flies is likely to reflect a similar number of female flies in the environment.

Mating after dispersal

Male Qfly use pheromones and acoustic signals to attract sexually receptive females, and mate only during a brief period of about 30 minutes at dusk (Tychsen and Fletcher 1971). Males gather on the upwind side of trees, where they release pheromone and fan their wings, directing the pheromone stream through the foliage (Tychsen 1977). Male calling is energetically expensive and calling in aggregations maximizes their chances of mating success (Weldon 2007). Males downwind of an aggregation might fly upwind in response to pheromone being released by calling males. There is a period of only about ten minutes during which males could fly to join the flying swarm (Tychsen 1977), and only enough time to mate once at each dusk, although males may mate in many dusk periods over their lifetime (Fay and Meats 1983, Radhakrishnan and Taylor 2008, Radhakrishnan *et al.* 2009). Males do not mate when temperatures at dusk are below 15°C with 50% of males mating at 20°C or higher temperatures (Meats and Fay 2000). Qfly have a relatively poor capacity to locate an odour source and it has been suggested that pheromones operate mainly within a single tree canopy (Meats and Hartland 1999, Weldon 2007). Acoustic cues are only effective over a short distance of about 50 cm (Mankin *et al.* 2004, 2008, Sivinski personal communication). Female Qfly move directly towards the males from up to 50 cm away (Tychsen 1977).

Odour plumes carried by light winds in trees usually become chaotic within a few centimetres of their source and provide few cues as to the direction of the source (Griffiths and Brady 1995). Qfly compensate for the diffused odour by making a series of short flights or walks (Meats and Hartland 1999) or by using large visual cues such as foliage to locate the source of odours (Dalby-Ball and Meats 2000). Female Qfly visit single male Qfly less frequently than aggregations (Weldon 2007). If the Qfly population is sparse, these limitations therefore result in single males being unlikely to attract a female and mate.

Meats (1998) estimated the chance of a successful mating between two Qfly on the same tree of 5 m × 5 m to be about 0.1%. Even in small cages, the chance of mating was only 0.8% (Fay and Meats 1983). A male Qfly has about a one in 400 chance of being in the right place at the right time if the density of males in the area was only one per hectare. Meats (1998) estimated that a single mating was probable when there were six male and six female Qfly present per hectare.

Current outbreak thresholds

Following the detection of small numbers of male Qfly (the number depends on the importing market), trading partners may fear that fruit harvested for trade could contain larvae that might establish populations in areas currently free from this pest. In Anon. (1996), a breeding population is considered to have three indicators. Two are direct indicators; larvae detected in fruit harvested within the area or a mated female detected in monitoring traps. In fruit fly free areas, larval searches are not routinely undertaken by regulatory authorities at times when no fruit flies are detected, although they are sometimes conducted to meet some importing country requirements. If present, larvae are generally detected and reported by the public but these are rare events in the FFEZ. Because of inefficiency and difficulty of detecting larvae, a monitoring grid or array has been established to provide an early warning of incursions by adult Qfly.

Qfly populations are known to occur naturally in about a 50:50 male:female ratio (Dominiak *et al.* 2008, Clarke and Dominiak 2010). In the FFEZ, female Qfly are poorly attracted to monitoring traps (Dominiak *et al.* 2003a, Dominiak 2006, Dominiak and Nicol 2010). However, these traps and lures may be more successful in tropical regions (Clarke and Dominiak 2010). Due to the lack of reliable female lures, the monitoring array relies primarily on the trapping of male flies and this is a common situation in most countries (International Atomic Energy Agency 2003). In Australia, Willison discovered that male Qfly are attracted to raspberry ketone and subsequently experimented with a related chemical, cuelure (Allman 1958). Cuelure breaks down into raspberry ketone and this process is accelerated in the presence of moisture (Metcalf 1990). Sexually mature male Qfly are attracted to raspberry ketone in nature (Tan and Nishida 1995). While male flies trapped may be sexually mature, there is no current technology which can indicate if a Qfly male has mated and therefore that a breeding population exists. In the absence of this technology, Bateman (1991) proposed that five male flies are an indicator of a breeding population and this is later supported by Meats (1998).

Conditions under the current code

Bateman (1991) and subsequently Anon. (1996) recommended that five male flies trapped within 1 km of each other within a 14 day period was an appropriate outbreak threshold, or in essence indicated unacceptable risk of a breeding population. This standard has been accepted for domestic trade within Australia and by many international trading partners. However, some countries choose lower outbreak thresholds. Presumably, these lower standards are thought to provide a higher level of assurance, but there have been no empirical studies to support this.

As part of the 5-fly standard in Anon. (1996), there is an intermediate step, presumably to further investigate for the presence of a breeding population. When two male flies are detected within one kilometre of each other within 14 days, 31 supplementary traps must be deployed within 200 metres (the outbreak zone) of the 2-fly detection and fruit must be checked for larvae. Supplementary traps must stay in place for nine weeks and be inspected twice weekly. If fewer than five male Qfly are trapped within 1 km within any 14 day period, an outbreak is not declared. In essence, it is deemed that a breeding population does not exist. If a total of five or more Qfly are detected within any 14 day period, an outbreak is declared for all domestic and international markets. After the outbreak declaration, no produce within the outbreak zone (within 200 m of the detection point) can be traded. All produce between 200 m and 15 km (the suspension area) must be treated with an approved disinfestation protocol before being transported into or sold in fruit fly sensitive markets (Jessup *et al.* 1998, De Lima *et al.* 2007).

The detection date of the last fly trapped is used to determine the reinstatement of area freedom based on generation tables in Anon. (1996). For some countries, these reinstatement periods vary from one generation plus 28 days, 12 weeks, three generations and one year. However apart from noting these differing standards, these reinstatement periods will not be discussed in detail further in this paper. Some countries have adopted the 2-fly threshold (within 400 m) as the outbreak threshold rather than the 5-fly threshold (within 1 km). For Australian exporters and regulators, the different outbreak thresholds result in disrupted trade and an administration burden. Moreover, the disparity in outbreak thresholds and reinstatement periods places regulatory authorities in a difficult position, needing to impose movement controls on host commodities destined for markets with different requirements.

Implications for different outbreak thresholds

Australian states and territories have agreed to the 5-fly threshold as an outbreak threshold. This agreement allows susceptible produce to be traded based on the specified conditions before or after an outbreak is declared. What happens when a trading partner requires a different threshold?

In the Australian response, the detection of two flies requires the deployment of supplementary traps and fruit searches. However since the Australian 5-fly outbreak threshold is not reached, no movement controls are imposed and fruit may move unrestricted from a 2-fly zone to any part of the pest free area or the rest of Australia. Further, no chemical control measures are deployed. This contrasts with countries that are more risk averse and use a 2-fly threshold. A fruit fly outbreak in any country normally requires an eradication response and movement controls. Since Australia does not deploy these responses for a 2-fly threshold, the interpretation by a 2-fly importing country is that potentially infested produce can move from the area immediately around the 2-fly threshold to any other district.

What is the Australian response to these mixed thresholds? Australia only imposes eradication or movement controls after a 5-fly threshold and therefore countries using the 2-fly threshold may deem the entire or part of the pest free area infested. Trade in fruit fly host commodities under area freedom arrangements into 2-fly sensitive markets is likely to cease for the entire or part of the pest free area. Costly phytosanitary treatments are usually required for these 2-fly markets. The alternative is that Australia aligns its trade standard with the 2-fly threshold, and moves to a lower universal outbreak threshold. This action would decrease fruit fly free trade because the 2-fly threshold is reached more frequently than the 5-fly threshold. Due to the difficulties in servicing markets with different outbreak thresholds, would markets currently accepting the 5-fly threshold then also align with the 2-fly threshold? This possible change in outbreak threshold results in potentially all countries accepting the lowest outbreak threshold. One country is even more risk averse, requiring a 1-fly threshold for Qfly. If this strategy was adopted internationally by all countries for all species, the 1-fly threshold would become an unreasonable burden on all international trade. This strategy would significantly increase pesticide use in field eradication programs and cause most fruit to be unnecessarily treated with undesirable impact on the environment; some chemicals such as methyl bromide are green house gases. There would be significant benefits in harmonizing outbreak thresholds, but empirical evidence is required to support a preferred universal threshold.

New information published since the early 1990s.

Bateman's (1991) report was the basis for the current thresholds for outbreaks and these were adopted as a code of practice (Anon. 1996). More data of Qfly outbreaks have been published since Bateman (1991) and Anon. (1996), and these more recent publications may prove instructive in assessing the relative merits of the 5-fly and 2-fly thresholds. The monitoring grid is either a 400 m array in towns or a 1000 m array in orchards (Anon. 1996, Meats 1998). Fruit flies are reported to rarely disperse as far as one kilometre over their lifetime (Maelzer 1990, Bateman 1991, Meats 1996, Dominiak *et al.* 2003b, Meats *et al.* 2003, 2006, Meats and Edgerton 2008, Weldon and Meats 2010, Gilchrist and Meats 2011). Given the large size of the FFEZ, we can then surmise that introductions of Qfly usually result from the carriage by humans of infested produce, and this is supported by assessment at roadblocks (Bateman 1972, Dominiak *et al*. 2000, Sved *et al*. 2003, Maelzer *et al.* 2004, Dominiak and Coombes 2009). Clift and Meats (2005) used Bayesian scenario analysis to show that introductions by local inhabitants contributed more to outbreaks than passing travellers. Most humans reside in urban areas and therefore the more intense monitoring array (400 m) in towns is a reflection of the greater risk (Meats 1998, Maelzer *et al*. 2004). Townships also provide better environments for survival and development of fruit flies than the surrounding rural areas (Yonow and Sutherst 1998, Raghu *et al*. 2000, Dominiak *et al.* 2006). Backyard environments are typically well watered and contain both sheltered microclimates and host fruit trees. Larger urban areas have an urban heat island which further minimizes the adverse effects of cold weather (Torok *et al*. 2001, Dominiak *et al.* 2006). The one kilometre grid is used in lower risk rural and orchard areas. These relatively sparsely populated rural areas are unlikely to be the first point of introduction of infested fruit and if they are, rural areas generally provide less favourable environments for fruit fly survival (Dominiak *et al.* 2006).

Meats (1998) suggests that a detection of two male flies within a two week period on the one kilometre grid represents a density between 2.1 and 6.57 flies per hectare within the outbreak zone (200 m radius from the discovery point). The upper estimate of 6.57 flies per hectare represents the most extreme situation in which the source of the incursion is directly in the centre of four adjacent traps in a grid, maximizing its distance from any trap. Meats (1998) proposed that when the density of flies within the outbreak zone exceeded six flies per hectare (of each sex), there was potential (albeit a very low risk) for one pair to mate. Superficially, the upper estimate of 6.57 flies per hectare appears to exceed the minimum density required for a mating to occur by 0.57 flies per hectare. However the theoretical minimum breeding density proposed by Meats (1998) of six male flies is an extremely conservative estimate and is essentially only a 'best guess' based on the information available at that time. Several critical factors used to obtain this theoretical minimum breeding estimate remain poorly understood. Meats (1998) estimated that the probability of a successful mating in the field was less than 0.1 although in calculating the minimum breeding density, the model assumed that it was equal to 0.1. This estimate of 0.1 was based on unpublished observations and has not been substantiated with data or confirmed experimentally in the field. The model also assumes that there are ten dusk periods available for mating and that mating can occur each and every dusk period.

Tychsen and Fletcher (1971) concluded that mating only occurs within a 30 minute period each day so that sexually mature flies must be in close proximity at this time for mating to occur. Meats (1998) acknowledges that his estimate of ten dusk periods is also too high as it does not take into account adverse weather, the inhospitable environment, and other factors unfavourable to fruit flies. In reality, mating will only occur under favourable conditions and in the presence of an adequate population. Another factor included in the estimate was dispersal behaviour observed by Fletcher (1973, 1974a, 1974b) in a commercial orchard at Wilton, New South Wales. Fletcher's conclusions are specific to the coastal environment where his study was conducted and cannot be directly applied to inland pest free areas that are much less favourable to fruit flies (Dominiak *et al*. 2006). Meats (1998) also acknowledged in his closing remarks that verification of the models is still required and to date this issue remains unresolved. Meats (1998) recognized that his interpretation of trapping rates on the 1 km grid is conservative, and accordingly did not recommend that the detection of two flies should be the threshold for quarantine precautions, but rather a threshold to intensify the grid.

Data for 2007–2009 period

The period from February 2007 to April 2009 was chosen as a base to compare 2-fly and 5-fly thresholds. Information was provided by the state departments of agriculture in Victoria and New South Wales; there were no outbreaks in the South Australian portion of the FFEZ during this period. Climatically, autumn 2007 experienced near neutral values for the Southern Oscillation Index (SOI) with most parts of New South Wales and Victoria receiving average rainfall (Braganza 2008). The study area received slightly above average rainfall in spring and summer of 2007 followed by dry conditions in autumn, winter and spring 2008 (Duell 2009, Qi 2009). Average to below average rainfall occurred in the FFEZ in summer 2008–2009 and autumn 2008 however several exceptional heatwaves occurred in February 2009 (Mullen 2009). In this period, there were 27 outbreaks and these were allocated to one of two categories.

Category A was a response after detection of two flies, where 31 supplementary traps were deployed and larval searches undertaken according to Anon. (1996). No eradication or product movement controls were imposed. Trade to countries using the 2-fly threshold would have been suspended for that area. Trade was reinstated only after no flies were trapped for a period of one generation plus 28 days. There was no restriction of trade with any Australian states or any 5-fly markets. There were 19 outbreaks in this category (Victoria: Invergorden 18 March 2008; Cobram 12 March 2008; Barooga 13 March 2008; Shepparton 10 April 2008; Bunbartha 11 April 2008; Katunga 14 April 2008; Numurkah 15 April 2008; Cobram East 2 June 2008; Echuca 18 September 2008; Irymple 24 March 2009. New South Wales: Yenda 11 April 2007; Darlington Point 26 April 2007; Yanco 29 May 2007; Lake Wyangan 12 March 2008; Hillston town 15 April 2008; Yenda 16 April 2008; Yanco 16 September 2008; Leeton town 16 September 2008; Hillston orchard 22 September 2008).

Category B was based on a 5-fly threshold. Subsequent procedures were according to Anon. (1996); supplementary traps and larval searches were conducted, eradication programs and product movement controls were initiated, and a 15 km suspension zone was established. Trade in fruit fly free produce to all domestic and international markets (including countries using the 2-fly threshold) was suspended for all host commodities grown within the suspension zone until there were no flies trapped for one generation plus 28 days. There were eight outbreaks in this category (Victoria: Koonoomoo 2 February 2007; Invergordon 20 March 2008; Bunbartha 22 April 2008; Katunga 13 May 2008; Cobram East 19 June 2008; Shepparton 3 April 2009. New South Wales; Narrandera 23 May 2007; Yanco 28 October 2008.)

Of the 27 outbreaks, 19 Category A outbreaks (70.4% of all outbreaks) did not progress to a Category B outbreak despite supplementary trapping and larval searches. Even with the low level of progression to the 5-fly threshold (29.6%), all susceptible host produce from the pest free area required disinfestation before being exported to markets requiring any threshold other than the 5-fly threshold. Meats *et al.* (2003) found 71% of single Qfly detections did not lead to 5-fly outbreaks and self extinguished without any eradication response. The 2007–2009 data for the 2-fly threshold of 70.4% is consistent with Meats *et al*. (2003).

Riverina trade volume since 1996

There has been considerable trade in host produce from the FFEZ since 1996 using the 5-fly threshold without any reports of larvae found in produce. This confirms that area freedom certification procedures for Australia's pest free area are robust given that consumers are highly likely to report and return damaged fruit to retailers. The volume of produce varies from year to year. Australian Bureau of Statistics (2008) reported that, for the statistic local areas of Carrathool, Griffith, Leeton and Murrumbidgee, 8586, 166 689 and 172 387 tonnes of stone fruit, oranges and other citrus respectively was produced. These combined industries are valued at $86.492 M (Australian Bureau of Statistics 2008). Given the volume and value of fruit traded annually, if the 2-fly threshold was an accurate indicator of crop infestation, it is likely that Qfly would have been detected in consignments in domestic or international market during the past 15 years.

Closing comments

Qfly is recognized as a poor colonizer in fruit fly free areas such as the FFEZ, owing to hostile conditions for survival and reproduction (Bateman 1972, 1977, Fletcher 1987, Edge *et al.* 2001, Meats *et al.* 2003, Weldon 2007). Even introduction by human activity (jump dispersal) very rarely results in establishment (Maelzer *et al.* 2004, Meats and Edgerton 2008). Given the large volume of produce traded without incident, the 5-fly threshold has a proven track record of success in providing highly effective phytosanitary assurance. Based on the evaluation of outbreak data, there is no indication that the 2-fly threshold provides any additional assurance. On this basis, we recommend that international trading partners adopt the 5-fly threshold as a universal threshold that provides a high level of assurance and also enables increased trading opportunity.

Acknowledgments

The authors would like to thank the many trap inspectors who inspect and report on fly detections in Victoria and New South Wales. The identification services in both states are also greatly appreciated. The administration and Information and Communications Technology services in state Departments also make a significant contribution to maintaining and reporting of databases which provided the information in this paper. Earlier versions of this manuscript were improved by comments from Satendra Kumar, Sarah Sullivan, Lionel Hill and Associate Prof Phil Taylor.

References

Allman, S.L. (1958). Queensland fruit fly. New South Wales Department of Agriculture. Conference of Commonwealth and State Entomologists. Brisbane, May 1957. Commonwealth Scientific and Industrial Research Organisation, pp. 68-70.

Allwood, A. (2000). Regional approach to the management of fruit flies in the Pacific Island countries and territories. *In* 'Area-wide control of fruit flies and other insect pests', ed. K.H. Tan, pp. 439-48. (Penerbit Universiti Sains Malaysia, Penang).

Anon. (1996). Code of practice for the management of Queensland fruit fly. Standing Committee on Agriculture and Resource Management, Department of Primary Industries, Canberra.

Australian Bureau of Statistics (2008). Agricultural commodities: small area data, Australia, 2005–2006. Report 71250DO003.

Bateman, M.A. (1972). The ecology of fruit flies. *Annual Review of Entomology* 17, 493-518.

Bateman, M.A. (1977). Dispersal and species interactions as factors in the establishment and success of tropical fruit flies in new areas. *Proceedings of the Ecological Society of Australia* 10, 106-12.

Bateman, M.A. (1991). The impact of fruit flies on Australian horticulture. Horticultural Policy Council Report No. 3. ISBN 0642161100.

Braganza, K. (2008). Seasonal climate summary southern hemisphere (autumn 2007): La Nina emerges as a distinct possibility in 2007. *Australian Meteorological Magazine* 57, 65-75.

Clarke, A.R. and Dominiak, B.C. (2010). Positive correlation of male and female *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) catches in orange-ammonia traps. *General and Applied Entomology* 39, 9-13.

Clarke, A.R., Powell, L.S., Weldon, C.W. and Taylor, P.W. (2011). The ecology of *Bactrocera tryoni* (Diptera: Tephritidae): what do we know to assist pest management? *Annals of Applied Biology* 158, 26-54.

Clift, A. and Meats, A. (2005). Use of a Bayesian Belief Network to identify situations that favour fruit fly incursions in inland SE Australia. International Congress on Modelling and Simulation MODSIM 2005, eds A. Zerger and R.M. Argent, pp. 170-6. (Modelling and Simulation Society of Australia and New Zealand).

Courtice, A.C. and Drew, R.A.I. (1984). Bacterial regulation of abundance in tropical fruit flies (Diptera: Trephritidae). *Australian Zoology* 21, 251-68.

Dalby-Ball, G. and Meats, A. (2000). Influence of the odour of fruit, yeast and cuelure on the flight activity of the Queensland fruit flies, *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae). *Australian Journal of Entomology* 39, 195-200.

De Lima, C.P.F., Jessup, A.J., Cruickshank, L., Walsh, C.J. and Mansfield, E.R. (2007). Cold disinfestation of citrus (*Citrus* spp.) for Mediterranean fruit fly (*Ceratitis capitata*) and Queensland fruit fly (*Bactrocera tryoni*) (Diptera: Tephritidae). *New Zealand Journal of Crop and Horticultural Science* 35, 39-50.

Dominiak, B.C. (2006). Review of the use of protein food based lures in McPhail traps for monitoring Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae). *General and Applied Entomology* 35, 7-12.

Dominiak, B.C., Campbell, M., Cameron, G. and Nicol, H. (2000). Review of vehicle inspection historical data as a tool to monitor the entry of hosts of Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) into a fruit fly free area. *Australian Journal of Experimental Agriculture* 40, 763-71.

Dominiak, B.C. and Coombes, N.M. (2009). Fruit carrying characteristics of travellers into a quarantine zone in New South Wales in 1999/2000. *Plant Protection Quarterly* 24, 14-19.

Dominiak, B.C., Gilmour, A.R., Kerruish, B. and Whitehead, D. (2003a). Detecting low populations of Queensland fruit fly *Bactrocera tryoni* (Froggatt) with McPhail and Lynfield traps. *General and Applied Entomology* 32, 49-53.

Dominiak, B.C., Mavi, H.S. and Nicol, H.I. (2006). Effect of town microclimate on the Queensland fruit fly *Bactrocera tryoni*. *Australian Journal of Experimental Agriculture* 46, 1239-49.

Dominiak, B.C., McLeod, L.J. and Landon, R. (2003b). Further development of a low-cost release method for sterile Queensland fruit fly, *Bactrocera tryoni* (Froggatt) in rural New South Wales. *Australian Journal of Experimental Agriculture* 43, 407-17.

Dominiak, B.C. and Nicol, H.I. (2010). Field performance of Lynfield and McPhail traps for monitoring male and female sterile (*Bactrocera tryoni* Froggatt) and wild *Dacus newmani* (Perkins). *Pest Management Science* 66, 741-4.

Dominiak, B.C., Sundaralingham, S., Jiang, L., Jessup, A.J. and Barchia, I.M. (2008). Production levels and life history traits of mass reared Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) during 1999/2002 in Australia. *Plant Protection Quarterly* 23, 131-5.

Drew, R.A.I. (1974). The responses of fruit fly species (Diptera: Tephritidae) in the South Pacific area to male attractants. *Journal of the Australian Entomological Society* 13, 267-70.

Drew, R.A.I. (1987). Behavioural strategies of fruit flies of the genus *Dacus* (Diptera: Tephritidae) significant in mating and host-plant relationships. *Bulletin of Entomological Research* 77, 73-81.

Drew, R.A.I. (1989). The tropical fruit flies (Diptera: Tephritidae) of the Australasian and Oceanian regions. *Memoirs of the Queensland Museum.* 26, 1-521.

Drew, R.A.I. and Lloyd, A.C. (1987). Relationship of fruit flies (Diptera: Tephritidae) and their bacteria to host plants. *Annals of the Entomological Society of America* 80, 629-36.

Drew, R.A.I., Zalucki, M.P. and Hooper, H.H.S. (1984). Ecological studies of Eastern Australia fruit flies (Diptera: Tephritidae) in their endemic habitat. I. Temporal variation in abundance. *Oecologia* (Berlin) 64, 267-72.

Duell, R. (2009). Seasonal climate summary southern hemisphere (autumn 2008): a return to neutral ENSO conditions in the tropical Pacific. *Australian Meteorological and Oceanographic Journal* 58, 63-77.

Edge, V., Gardner, R., Green, A., Cock, K. and Cornish, J. (2001). Technical review of the Tri-State Strategy for Queensland Fruit Fly. Report to Standing Committee on Agriculture and Resource Management. January 2001, 62 pp.

Ero, M.M., Hamacek, E. and Clarke, A.R. (2011). Foraging behaviours of *Diachasmimorpha kraussi* (Fullaway) (Hymenoptera: Braconidae) and its host *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) in a nectarine (*Prunus persica* (L.) Batsch var. *nectarina* (Aiton) Maxim) orchard. *Australian Journal of Entomology* 50, 234-40.

Fanson, B.G., Weldon, C.W., Perez-Staples, D., Simpson, S.J. and Taylor, P.W. (2009). Nutrients, not caloric restriction, extend lifespan in Queensland fruit flies (*Bactrocera tryoni*). *Aging Cell* 8, 1-10.

Fay, H.A.C. and Meats, A. (1983). The effects of age, ambient temperature, thermal history and mating history on mating frequency in males of the Queensland fruit fly, *Dacus tryoni*. *Entomologia Experimentalis et Applicata* 35, 273-6.

Fletcher, B.S. (1973). The ecology of a natural population of the Queensland fruit fly, *Dacus tryoni* IV. The immigration and emigration of adults. *Australian Journal of Zoology* 21, 541-65.

Fletcher, B.S. (1974a). The ecology of a natural population of the Queensland fruit fly, *Dacus tryoni* V. The dispersal of adults. *Australian Journal of Zoology* 22, 189-202.

Fletcher, B.S. (1974b). 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, 353-63.

Fletcher, B.S. (1987). The biology of dacine fruit flies. *Annual Review of Entomology* 32, 115-44.

Fletcher, B.S. (1989). Movements of tephritid fruit flies. *In* 'Fruit flies, their biology, natural enemies and control' Vol. 3B, eds A.S. Robinson and G. Hooper, pp. 209-19. (Elsevier, Amsterdam).

Gilchrist, A.S. and Meats, A.W. (2011). Factors affecting the dispersal of large-scale releases of the Queensland fruit fly, *Bactrocera tryoni*. *Journal of Applied Entomology* 37, 186-8.

Griffiths, N. and Brady, J. (1995). Wind structure in relation to odour plumes in tsetse fly habitats. *Physiological Entomology* 20, 286-92.

Hancock, D.L., Hamacek, E.L., Lloyd, A.C. and Elson-Harris, M.M. (2000). The distribution and host plants of fruit flies (Diptera: Tephritidae) in Australia. DPI Publications, Brisbane, Australia. ISSN 0727-6273.

International Atomic Energy Agency (2003). Trapping guidelines for area-wide fruit fly programmes. International Atomic Energy Agency, Vienna. pp. 47.

Jessup, A.J., Carswell, I.F. and Dalton, S.P. (1998). Disinfestation of fresh fruits from *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) with combination mild heat and modified atmosphere packaging. *Australian Journal of Entomology* 37, 186-8.

Li, B., Ma, J., Hu, X., Liu, H., Wu, J., Chen, H. and Zhang, R. (2010). Risk of introducing exotic fruit flies, *Ceratitis capitata*, *Ceratitis cosyra* and *Ceratitis rosa* (Diptera: Tephritidae), into southern China. *Journal of Economic Entomology* 103, 1100-11.

Maelzer, D.A. (1990). Fruit fly outbreaks in Adelaide, S.A., from 1948–49 to 1986–87. I. Demarcation, frequency and temporal patterns of outbreak. *Australian Journal of Zoology* 38, 439-52.

Maelzer, D.A., Bailey, P.T. and Perepelicia, N. (2004). Factors supporting the non-persistence of fruit fly populations in South Australia. *Australian Journal of Experimental Agriculture* 44, 109-26.

Mankin, R.W., Anderson, J.B., Mizrach, A., Epsky, N.D., Shuman, D., Heath, R.R., Mazor, M., Hetzroni, A., Grinshpun, J., Taylor, P.W. and Garrett, S.L. (2004). Broadcasts of wing-fanning vibrations recorded from calling male *Ceratitis capitata* (Diptera: Tephritidae) increases captures of females in traps. *Journal of Economic Entomology* 97,1299-309.

Mankin, R.W., Lemon, M., Harmer, A.M.T., Evans, C.S. and Taylor, P.W. (2008). Time-pattern and frequency analyses of sounds produced by irradiated and untreated male *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) during mating behaviour. *Annals of the American Entomological Society* 101, 664-74.

Meats, A. and Fay, F.A.C. (2000). Distribution of mating frequency among males of the Queensland fruit fly, *Bactrocera tryoni* (Froggatt), in relation to temperature, acclimation and change. *General and Applied Entomology* 29, 27-30.

Meats, A. and Hartland, C.L. (1999). Upwind anemotaxis in response to cue-lure by the Queensland fruit fly *Bactrocera tryoni*. *Physiological Entomology* 24, 90-7.

Meats, A. and Smallridge, C.J. (2007). Short and long range dispersal of Medfly, *Ceratitis capitata* (Diptera: Tephritidae) and its invasive potential. *Journal of Applied Entomology* 8, 518-23.

Meats, A., Smallridge, C.J. and Dominiak, B.C. (2006). Dispersion theory and the sterile insect technique: application to two species of fruit fly. *Entomologia Experimentalis et Applicata* 119, 247-54.

Meats, A.M. (1996). Demographic analysis of sterile insect trials with Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae). *General and Applied Entomology* 27, 2-12.

Meats, A.M. (1998). The power of trapping grids for detecting and estimating the size of invading propagules of the Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) risks of subsequent infestation. *General and Applied Entomology* 28, 47-55.

Meats, A.M., Clift, A.D. and Robson, M.K. (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.

Meats, A.M. and Edgerton, J.E. (2008). Short- and long-distance dispersal of Queensland fruit fly, *Bactrocera tryoni* and its relevance to invasive potential, sterile insect technique and surveillance trapping. *Australian Journal of Experimental Agriculture* 48, 1237-45.

Metcalf, R.L. (1990). Chemical ecology of Dacine fruit flies (Diptera: Tephritidae). *Annals of the Entomological Society of America* 83, 1017-30.

Mullen, C. (2009). Seasonal climate summary southern hemisphere (summer 2008-09): a weak, brief La Nina returns. Bumper wet season in tropical Australia: exceptional heatwaves in southeastern Australia. *Australian Meteorological and Oceanographic Journal* 58, 275-84.

Oliver, J. (2007). Summary of national fruit fly-related activities released. Plant Protection News. February 2007. Department of Agriculture, Fisheries and Forestry.

Perez-Staples, D., Harmer, A.M.T., Collins, S.R. and Taylor, P.W. (2008). Potential for pre-release diet supplements to increase the sexual performance and longevity of male Queensland fruit flies. *Agricultural and Forest Entomology* 10, 255-62.

Perez-Staples, D., Prabhu, V. and Taylor, P.W. (2007). Post-teneral protein feeding enhances sexual performance of Queensland fruit flies. *Physiological Entomology* 32, 127-35.

Plant Health Australia (2010). National Plant Biosecurity Strategy. Plant Health Australia, Deakin, Australian Capital Territory.

Prabhu, V., Pérez-Staples, D. and Taylor, P.W. (2008). Protein: carbohydrate ratios promoting sexual activity and longevity of male Queensland fruit flies. *Journal of Applied Entomology* 132, 575-82.

Qi, L. (2009). Seasonal climate summary southern hemisphere (spring 2008): La Nina pattern returning across equatorial Pacific. *Australian Meteorological and Oceanographic Journal* 58, 199-208.

Radhakrishnan, P., Perez-Staples, D., Weldon, C.W. and Taylor, P.W. (2009). Multiple mating and sperm depletion in male Queensland fruit flies: effects on female remating behaviour. *Animal Behaviour* 78, 839-46.

Radhakrishnan, P. and Taylor, P.W. (2008). Ability of male Queensland fruit flies to inhibit receptivity in multiple mates, and the associated recovery of accessory glands. *Journal of Insect Physiology* 54, 421-8.

Raghu, S., Clarke, A.R., Drew, R.A.I. and Hulsman, K. (2000). Impact of habitat modification on the distribution and abundance of fruit flies (Diptera: Tephritidae) in southeast Queensland. *Population Ecology* 42, 153-60.

Stanaway, M.A., Zalucki, M., Gillespie, P.S., Rodriguez, C.M. and Maynard, G.V. (2001). Pest risk assessment of insects in sea cargo containers. *Australian Journal of Entomology* 40, 180-92.

Sved, J.A., Yu, H., Dominiak, B. and Gilchrist, A.S. (2003). Inferring modes of colonization for pest species using heterozygosity comparisons and shared-allele test. *Genetics* 163, 823-31.

Stephenson, B.P., Gill, G.S.C., Randall, J.L. and Wilson, J.A. (2003). Biosecurity approaches to surveillance and response for new plant pest species. *New Zealand Plant Protection* 56, 5-9.

Tan, K.H. and Nishida, R. (1995). Incorporation of raspberry ketone in the male rectal glands of the Queensland fruit fly *Bactrocera tryon*i Froggat (Diptera: Tephritidae). *Applied Entomology and Zoology* 30, 494-7.

Torok, S.J., Morris, J.G., Skinner, C. and Plummer, N. (2001). Urban heat island features of southeast Australian towns. *Australian Meteorological Magazine* 50, 1-13.

Tychsen, P.H. (1977). Mating behaviour of the Queensland fruit fly, *Dacus tryoni* (Diptera: Tephritidae), in field cages. *Journal of the Australian Entomological Society* 16, 459-65.

Tychsen, P.H. and Fletcher, B.S. (1971). Studies on the rhythm of mating in the Queensland fruit fly, *Dacus tryoni*. *Journal of Insect Physiology* 17, 2139-56.

Weldon, C. (2003). Effectiveness of coloured unbaited sticky traps for monitoring dispersal of gamma-irradiated Queensland fruit fly *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae). *General and Applied Entomology* 32, 55-60.

Weldon, C. (2007). Influence of male aggregation size on female visitation in *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae). *Australian Journal of Entomology* 46, 29-34.

Weldon, C. and Meats, A. (2007). Short-range dispersal of recently emerged males and females of *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) monitored by sticky sphere traps baited with protein and Lynfield traps baited with cue-lure. *Australian Journal of Entomology* 46, 160-6.

Weldon, C. and Meats, A. (2010). Dispersal of mass-reared sterile, laboratory-domesticated and wild male Queensland fruit flies. *Journal of Applied Entomology* 134, 16-25.

Weldon, C.W., Prenter, J. and Taylor, P.W. (2010). Activity patterns of Queensland fruit flies (*Bactrocera tryoni*) are affected by both mass-rearing and sterilization. *Physiological Entomology* 35, 148-53.

Weldon, C.W. and Taylor, P.W. (2010). Desiccation resistance of adult Queensland fruit flies *Bactrocera tryoni* decreases with age. *Physiological Entomology* 35, 385-90.

Weldon, C.W. and Taylor, P.W. (2011). Sexual development of wild and mass-reared male Queensland fruit flies in response to natural food sources. *Entomologia Experimentalis et Applicata* 139, 17-24.

White, I.M. and Elson-Harris, M.M. (1992). 'Fruit flies of economic significance: their identification and bionomics'. (CAB International, Oxon, UK).

Yonow, T. and Sutherst, R.W. (1998). The geographical distribution of the Queensland fruit fly, *Bactrocera (Dacus) tryoni*, in relation to climate. *Australian Journal of Agricultural Research* 49, 935-53.