

Area-wide management of fruit flies (Diptera: Tephritidae) in the Central Burnett district of Queensland, Australia

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ABSTRACT

Queensland fruit fly, *Bactrocera tryoni* (Froggatt), is the most serious pest of the native tephritid species in Australia and a significant market access impediment for fruit commodities from any area where this species is endemic. An area-wide management (AWM) program was implemented in the Central Burnett district of Queensland with the aim of improving fruit fly control and enhancing market access opportunities for citrus and other fruits produced in the district. The primary control measures adopted in the AWM system included bait spraying of commercial and non-commercial hosts and the year-round installation of male annihilation technology (MAT) carriers in both orchards and town areas. The MAT carrier used consisted of a dental wick impregnated with 1 ml cue-lure [4-(4-acetoxyphenol)-2-butanone] and 1 ml Malathion 500 EC in a plastic cup. The application of these control measures from 2003 to 2007 resulted in overall suppression of fruit fly populations across the entire district. Male trap catches at the peak activity time were reduced by 95% and overall fruit fly infestation in untreated backyard fruit of town areas reduced from 60.8% to 21.8%. Our results demonstrate remarkable improvement in fruit fly control and economic benefit to the Central Burnett horticulture. Therefore, commercial growers are continuing the AWM program as a long-term, industry funded activity, to provide an additional layer of phytosanitary security for market access of fruit commodities from this district.

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1. Introduction

Area-wide management (AWM) is implemented to control the total population of a pest species within a delimited geographic area (Lindquist, 2000; Hendrichs et al., 2007). Management measures are often applied over all infestation sites in the areas of concern to limit the probability of reinfestation by immigrants from unmanaged habitats (Elliott et al., 2008). AWM has often been used as a systems approach to control pest fruit fly species. Case studies with the melon fly, *Bactrocera cucurbitae* (Coquillett), and the Mediterranean fruit fly, *Ceratitidis capitata* (Wiedemann), in Hawaii (Mau et al., 2007; Vargas et al., 2008); the oriental fruit fly, *B. dorsalis* Hendel, and the guava fruit fly, *B. correcta* Bezzi, in Thailand (Orankanok et al., 2007); and the oriental fruit fly in Taiwan (Chiang et al., 2007) have demonstrated the effectiveness of implementing AWM strategies under different circumstances.

In Australia, AWM has been used primarily to tackle incursions of pest fruit fly species into areas where they did not exist

previously. Examples include eradicating the introduced exotic species, the papaya fruit fly, *B. papayae* Drew & Hancock, from north Queensland in 1999; eradicating Queensland fruit fly, *B. tryoni* (Froggatt), from Western Australia in 1989; maintaining freedom from endemic fruit flies in the Fruit Fly Exclusion Zone of southern states; and ongoing population suppression in buffer zones around the exclusion areas (Jessup et al., 2007). In this paper we describe the area-wide management of fruit flies in the Central Burnett district of Queensland, representing the first attempt to implement a large-scale AWM program against native fruit fly species in an area with moderate to high endemic populations in Australia (Drew, 1989; Hancock et al., 2000).

In the Central Burnett district, *B. tryoni* is the major pest tephritid species of citrus and other fruits although its sibling species, *B. neohumeralis* (Hardy), may also cause some damage (Fitt, 1989). Because of the fruit fly free areas in other parts of Australia, domestic trade in fruit fly host commodities from areas such as the Central Burnett is subject to strict quarantine requirements under the management of the Australian Domestic Quarantine and Market Access Working Group. Protocols, involving preharvest, postharvest or both types of treatment, are evaluated, approved and monitored under an Interstate Certification Assurance (ICA)

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system. For many years, postharvest chemical treatments with dimethoate have been widely used under this system for a variety of fruit fly host commodities including Central Burnett citrus. In 1999, as the result of Queensland research referred to elsewhere in this paper, an alternative protocol for Central Burnett citrus (ICA-28), without the need for dimethoate postharvest treatment, was developed. At the commencement of the AWM program described here, Victoria was the only state which had accepted ICA-28. This protocol allowed Central Burnett citrus to access Victorian markets during the period from March 1 to August 25 based on a weekly preharvest baiting program from 12 weeks prior to harvest until the end of harvest followed by postharvest inspection.

In the Central Burnett, field sprays with dimethoate, in conjunction with baiting, are generally required to reduce fruit fly infestation in other commercial hosts such as mangoes, table grapes, peaches and nectarines that are harvested in the spring/summer seasons when fruit fly populations in the district are high. Additional postharvest treatments of fruit with dimethoate may also be required for some markets. However, both preharvest and postharvest use of dimethoate has been under review (<http://www.apvma.gov.au>). The potential restrictions on use of this chemical therefore require alternative market access protocols based on higher levels of field control for quarantine pest fruit flies.

The AWM program was aimed at improving fruit fly control and enhancing market access opportunities for citrus and other fruits by incorporating multiple control measures across the Central Burnett district. The AWM strategies were based on improving and expanding existing bait application and the introduction of male annihilation technology (MAT) in commercial orchards and the application of both strategies to town areas. These measures specifically targeted the rapid increase of fruit fly activities in the district and the population growth in untreated summer fruiting hosts, particularly in town areas, thereby alleviating pest pressure on the major economic crops of winter/spring citrus and summer table grapes in the district.

2. Materials and methods

2.1. Study area

The Central Burnett is a major citrus-growing district in Queensland, with an area of approximately 70 km by 12 km which includes the towns of Gayndah (population 2500) and Mundubbera (population 2000). The district has 2000 hectares of citrus crops spread across 71 orchards, 370 hectares of table grapes, 50 hectares of mangoes, and small plantings of peaches, nectarines and avocados. The majority of commercial orchards are situated along the Burnett, Boyne and Auburn Rivers and their tributaries. The surrounding district comprises a mix of dry sclerophyll forest and grazing land. Most citrus crops in the district mature and are harvested in autumn (March–May), winter (June–August) and early spring (September). The citrus industry mainly produces fresh fruit for both domestic and export markets, with mandarins making up the largest share of production.

The activity of tephritid fruit flies was relatively low during most of the citrus maturing/harvesting period, but fruit fly numbers rapidly increased across the entire district at the end of citrus season from late August to early September (Lloyd et al., 2000). This coincided with warm spring temperatures and with reduced bait application as many citrus orchards had been harvested by that time of the season. The spring fruit fly pressure increased the risk of infestation in the high value, late season Murcott mandarin crop. Furthermore, there were large numbers of summer fruiting hosts (e.g. loquats, mangoes and stone fruit) in residential backyards in the town areas. As these urban fruit hosts were mostly untreated,

they became “breeding hot spots” generating high fruit fly populations that threatened summer commercial crops and carried over into the next citrus season (Lloyd et al., 2000, 2003). To maintain an acceptable level of fruit fly control, regular weekly baiting from January to September had been employed in most citrus orchards of the district before the AWM program commenced. This baiting application was part of an established integrated pest management (IPM) system in the district (Smith et al., 1997). At times of high fly pressure, additional insecticide cover sprays were applied although such practices were not compatible with the release of commercially reared beneficial insects used in the IPM system.

2.2. Preparation and organisation for the AWM program

Trapping and host survey activities were undertaken in the Central Burnett district prior to the AWM program. These early surveys were aimed at providing empirical data on the seasonal pattern of fruit fly activity and population breeding hot spots in the district for planning and implementing the AWM program. A district-wide monitoring program commenced in February 1999 and continued for 12 months, in which 51 cue-lure [4-(4-acetoxypheyl)-2-butanone] traps for both *B. tryoni* and *B. neohumeralis* were installed across the district. Concurrent sampling of non-commercial fruit representing 49 different plant species was carried out to assess fruit fly infestation. Fruit samples were collected in town backyards, along water courses and in other areas of native vegetation in an attempt to identify potential wild hosts in the district. From August 2002 to August 2003, a similar trapping program was undertaken with 40 cue-lure traps across the district. During this period, fruit collections were concentrated on potential summer hosts in the town areas of Gayndah and Mundubbera.

In May 2002, Central Burnett Area-Wide Management Committee (CBAWMC) was formed to manage the AWM program. The CBAWMC included researchers from Queensland Primary Industries and Fisheries (QPIF), district crop consultants, local government representatives, citrus and non-citrus growers and other industry stakeholders in the district. Prior to commencement of the AWM program in July 2003, the CBAWMC conducted extensive community and grower education activities to ensure all stakeholders in the district were informed of the program objectives and the funding mechanism. Written information was distributed to all orchard and town properties and numerous articles on the program were published in the local media. An easily identified name and logo (“Fruit Fly Force”) were designed for promoting all AWM activities.

2.3. Treatments in orchards

Three control measures, i.e. protein baiting, MAT and orchard hygiene, were implemented in both citrus and non-citrus orchards. Although the non-citrus crops (e.g. mangoes, table grapes and stone fruit) together represent less than 20% of the total horticulture in the district, fruit in these summer crops mature at times of peak fruit fly activity. Therefore, they have a greater risk of infestation than citrus and hence the potential to contribute significantly to the build-up of fruit fly populations and to increase the risk of infestation in subsequent autumn–winter citrus crops.

Weekly protein baiting commenced in January until 4 weeks after harvest for citrus and from the middle stage of fruit development to harvest for non-citrus crops. Initially, three bait formulation options (Table 1) were available for use in commercial orchards. The fruit fly bait was applied as a coarse spray to either a spot or strip of foliage as specified on the product label (equivalent to approximately 15–20 l of bait mixture per hectare).

Table 1
Fruit fly bait options for use in commercial orchards before Naturalure Fruit Fly Bait Concentrate® (Dow AgroSciences) was registered and became commercially available in late 2005.

Water	+	Fruit fly lure (autolysed protein)	+	Chlorpyrifos 750 g/kg Lorsban 750 WG	OR	Trichlorfon 500 g/l Dipterex 500 SL	OR	Maldison 1150 g/l Hy-Mal
100 l		2 l		267 g		780 ml		435 ml
Recommended rate as per insecticide product label				50–100 ml of mixture per tree as a strip or patch		50–120 ml of mixture per tree as a coarse spray		50–100 ml of mixture per tree as a strip or patch
Application as per registered use.								(15–20 l/ha applied as a band at skirt level for citrus)

Alternate sides of trees were baited to minimise the possibility of any phytotoxicity effects on fruit that came in contact with bait droplets (Lloyd et al., 2003).

Growers were strongly advised not to apply bait sprays to grass between rows because baits applied to host trees 1–1.5 m above ground had been shown to attract approximately 30 times more flies than baits applied to grass at the ground level (QPIF unpublished data). Bait sprays were timed according to the fruit stage rather than the trap catch of male fruit flies. In late 2005, Naturalure Fruit Fly Bait Concentrate® (Dow AgroSciences) was registered and became commercially available. The development and testing of this bait has been described elsewhere (Moreno and Mangan, 2002; Mangan and Moreno, 2004; Mangan et al., 2006). Naturalure contains protein attractants and the insecticide spinosad and is organically certified with a 0 days withholding period. Naturalure was used at the recommended 1:6.5 dilution (as per the Australian label) and applied at a rate of 7.5 l of mixture/Ha (1 l Naturalure) as a strip or spot application (<http://www.dowagro.com/au/prod/naturalure.htm>).

MAT carriers were installed in commercial orchards year-round. The MAT carrier consisted of a dental wick impregnated with 1 ml cue-lure and 1 ml Malathion 500 EC in a custom made round plastic 'cup' (6 cm diameter and 2 cm high) ("Bugs for Bugs", Mundubbera, Australia). The cup has a solid top with an integrated hanger, open on the underside. A circle of retaining pegs hold a dental wick around the inside edge of the cup. Growers were advised to distribute 10 MAT carriers per hectare of orchards and to replace them with new ones three times a year, in February, May and November.

The removal of residual fruit from commercial orchards and from fruit trees in rural residential backyards was recommended since these fruits could provide ideal breeding spots for fruit flies, particularly after regular baiting had ceased at the end of the commercial harvest period. All property owners were also advised to remove feral host trees and to treat other hosts with protein baiting and MAT as in commercial orchards.

2.4. Treatments in town areas

To facilitate the implementation of treatments in town areas, technical officers from the Gayndah and Mundubbera Shire Councils were employed to carry out treatments in the two town areas after being trained by the research team. Treatments included installation of MAT carriers or monitoring traps, application of bait sprays to fruiting hosts and collection of fruit when available. Information from the surveys of town areas undertaken by the research team prior to the AWM program assisted these operators in identifying the properties with fruit fly host trees in backyards.

The Hy-Mal bait formulation was used in the town areas from July 2003 to late 2005, as registered for application, i.e. 43.5 ml Hy-Mal + 200 ml yeast autolysate protein per 10 l water (as per the Australian label). The bait was sprayed onto fruiting host trees as one 50 ml spot per moderate sized host tree and two or three 50 ml spots per larger host trees (e.g. mango trees) on a weekly basis. Bait

application was not undertaken on rainy days or when wind speed was higher than 12 km/h. From late 2005, Naturalure was used to replace the Hy-Mal formulation as a less toxic alternative for urban areas. It was applied at the same dilution as used in the orchards, with one 10 ml spot per moderate sized host tree and two or three 10 ml spots per larger host tree, on a weekly basis. MAT carriers were distributed at one per property in the town areas and 10 per hectare in other breeding areas along water courses or on public land. MAT carriers were renewed four times per year in February, May, August and November, respectively. In addition, property owners in the town areas were instructed to dispose of fallen fruit for elimination of fruit fly breeding.

2.5. Evaluation

Changes in fruit fly abundance during the AWM program were monitored with 37 cue-lure traps across the Central Burnett district. Six of these traps were installed in the Gayndah town area, five in the Mundubbera town area, 11 in the Mundubbera orchards, and six in the Gayndah orchards. All traps were at least 50 m distant from the MAT carriers. In addition, nine traps were installed at properties outside the treatment zone to act as indicator sites, three in the Binjour area located between Gayndah and Mundubbera towns and six in rural backyards to monitor fruit fly activities in locations well away from the treated commercial orchards or town areas. In each trap, a cotton wick dosed with 1 ml cue-lure and 1 ml of malathion (the same as the MAT devices) was secured in a well on the underside of a plastic lid. Traps were cleared on a weekly basis and lure wicks were replaced every 3 months. All trap catches were examined by the research team at the Indooroopilly Research Centre of QPIF.

Previous studies showed that infestation levels in commercial citrus orchards where regular bait sprays were applied were 0.029–0.047% at the 95% confidence level (Lloyd et al., 2000). Therefore, sampling commercial citrus would not provide sufficient data to demonstrate the efficacy of the control measures that were implemented under the AWM system. However, infestation levels in largely untreated backyard fruit in town areas were known to be high prior to the AWM program; thus infestation in these fruits was assessed to evaluate the effectiveness of AWM.

Fruit collection from backyard fruit trees in the two town areas commenced in spring 2003 and continued until autumn 2007. Fruit samples were also taken from the untreated host trees at the indicator trap sites. The level of fruit fly infestation in these fruit samples was estimated as the percent of samples infested and larval load per kilogram of infested fruit. Where possible, samples of 1–2 kg for larger fruit (e.g. mangoes or stone fruit) and 20–30 pieces of fruit for smaller fruit (e.g. mulberries) were taken. Fruit samples were held on small gauze-topped drip trays placed in large ventilated plastic containers with a layer of moist vermiculite in the bottom to act as a pupation medium. Each sample, irrespective of the numbers of fruit contained, was held separately at 25–26 °C and 60–70% relative humidity for 2–3 weeks for pupation of any fruit fly larvae present.

The vermiculite was sieved on a number of occasions to recover pupae which were then held until emergence of adult flies. Fruit flies and their parasitoids that emerged from individual fruit samples were identified and recorded. All fruit sample incubation and subsequent fly identification were carried out by the research team at the Indooroopilly Research Centre of QPIF.

At the end of the citrus season in 2005 an in-depth grower survey was conducted to evaluate the commercial benefits of the program and to determine the level of industry support for maintaining AWM as a long-term activity. At the conclusion of the 4-year implementation an independent economic analysis of the AWM program and of the proposed ongoing industry funded program was undertaken.

3. Results

3.1. Fruit fly activity and host infestation prior to the AWM program

Male trap catches from orchards, along the Burnett River and in the town areas of Gayndah and Mundubbera from February 1999 to January 2000 reflected the seasonal pattern of variation in fruit fly activity in the Central Burnett district prior to the AWM program (Fig. 1). The peak activity of fruit flies at different parts of the district started in late August to early September and persisted until early December. The maximum daily catches of male fruit flies were up to 240 flies per trap during the peak period while the average daily catches declined below 70 flies per trap during the rest of the summer season between January and March. The fruit fly activity was very low, often with nil flies caught, between April and July. Records of orchard trap catches in previous seasons, provided by district crop consultants, showed that this seasonal pattern of fruit fly activity was typical in the Central Burnett district although the severity of winter temperatures and the occurrence of rainfalls were likely to cause some variation. The trap catches from August 2002 to August 2003 confirmed that the pattern of seasonal changes in fruit fly activity in the district were similar from year to year, but catches decreased with the maximum daily number of 100 flies per trap at the peak activity time (Fig. 2). This decline was partially due to the distribution of MAT carriers by some commercial growers in the Gayndah area between late 2002 and mid 2003 prior to the commencement of the AWM program. The MAT application in their orchards had immediate effects on trap catches in all areas where MAT carriers were installed.

The species identification of these trap catches showed that *B. tryoni* accounted for 91.4% and 96.0%, *B. neohumeralis* for 5.4% and

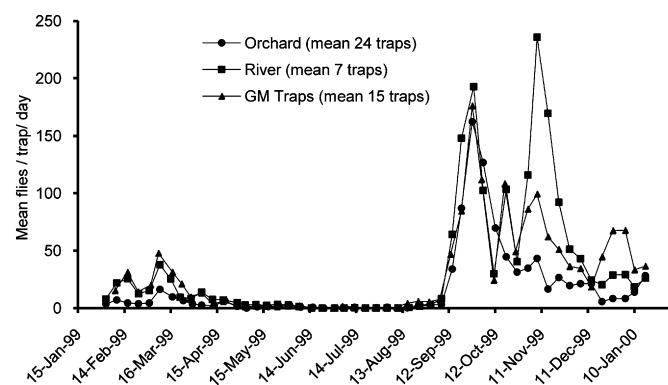


Fig. 1. Fruit fly catches from the cue-lure traps set up in orchards, along the river and in the towns of Gayndah and Mundubbera (GM traps) from February 1999 to January 2000. The data of this and the following figures include *Bactrocera tryoni* and *B. neohumeralis*.

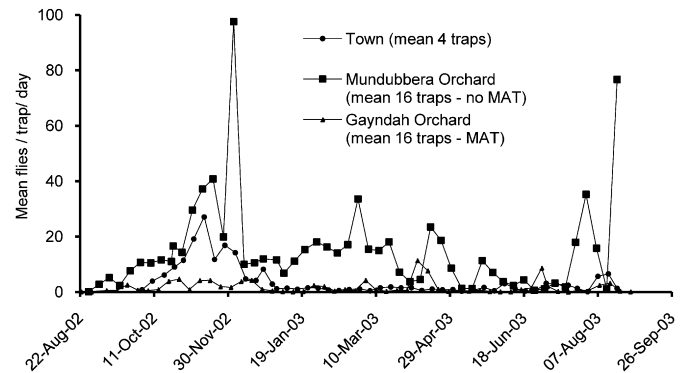


Fig. 2. Fruit fly catches from the cue-lure traps set up in orchards and towns of Gayndah and Mundubbera from August 2002 to August 2003.

2.0% in 1999 and 2002–2003, respectively. Seven other minor fruit fly species (i.e. *B. bryoniae*, *B. chorista*, *B. jarvisi*, *B. quadrata*, *Dacus aequalis*, *D. newmani*, and *Dirioxa pornia*) accounted for the rest of the trap catches.

The result of a district-wide host survey in 1999, based on collection and assessment of 253 samples of non-commercial fruit from 49 representative plant species showed that relatively few wild host trees were present in native vegetation areas and none was likely to contribute significantly to fruit fly abundance in the Central Burnett district (Lloyd et al., 2000). On the other hand, a survey in 2002–2003 found many host fruit trees in the town areas of Gayndah and Mundubbera, with the major ones being citrus (177 mainly mandarins, oranges, lemons and grapefruit), mango (453), cherry guava (16), guava (20), loquat (93) and mulberry (129). Of 92 fruit samples from 12 different species of host trees in the town areas, 60.8% were infested by fruit flies, with infestation in 100% of the mulberry, Brazilian cherry, loquat, cherry guava and stone fruit samples. Of the 5293 fruit flies reared from these fruit samples, 99.5% were *B. tryoni* and 0.5% *B. neohumeralis*.

3.2. Effects of AWM on fruit fly activity

In total, 25,000 MAT carriers were distributed across the Central Burnett district between August and November 2003, which contributed to a general reduction in fruit fly abundance. Under the AWM, the largest average daily trap catches were 1.5 flies in towns (Fig. 3a), 12 flies in orchards (Figs. 3b,c), and 13 flies at the indicator sites (Fig. 4). Overall, daily fruit fly catches in 37 cue-lure traps across all types of locations declined to 13 or less flies per trap at the peak activity time. This represents a reduction of approximately 95% in fruit fly activity, compared to peak trap catches prior to the commencement of the AWM program, although the seasonal patterns of fruit fly activity were similar before and during the AWM program.

The largest daily trap catches (i.e. 13 flies per trap) under the AWM were recorded in untreated stone fruit trees at one of the Binjour indicator sites in November 2005. The trap catches of fruit flies at this site were reduced in 2006–2007, which might have been caused by the scarcity of fruit on these trees due to the effect of prolonged drought in the district during this period. Larger fruit fly numbers were found in Mundubbera orchards in late 2006 than in the 3 previous years, possibly due to fruit fly breeding in the residual citrus that had not been removed and destroyed in some orchards. Assessment of residual fruit showed a high level of infestation in grapefruit (123.2 flies/kg fruit) and Murcott mandarins (35.3 flies/kg fruit) though lower in oranges (3.0 flies/kg fruit). However, in spite of these isolated “hot spots”, the average daily

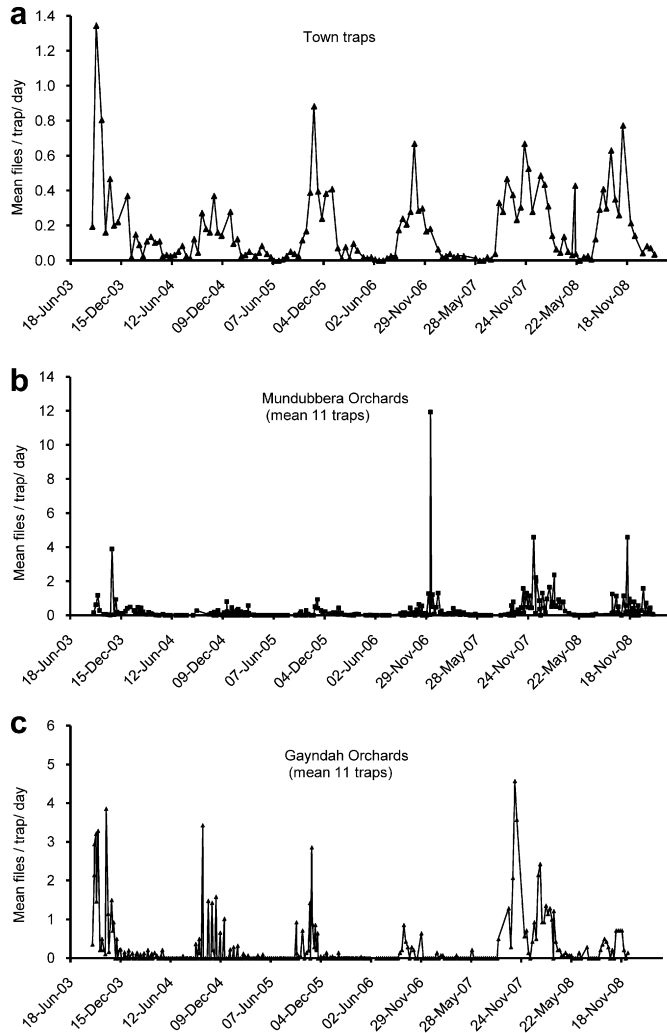


Fig. 3. Fruit fly catches from the cue-lure traps set up in towns and orchards under the area-wide management program from June 2003 to February 2009: a. towns; b. Mundubbera orchards; c. Gayndah orchards.

catches across the district from early 2007 to early 2009 remained at the level of less than five fruit flies per trap.

A total of 11,378 flies from 37 cue-lure traps were obtained from July 2003 to February 2007. Seven species of fruit flies were identified from these trap catches. The two pest species, *B. tryoni* and *B. neohumeralis* accounted for 90.6% and 3.5% of the total catches, respectively, whereas five non-pest species *B. bryoniae* (Tryon),

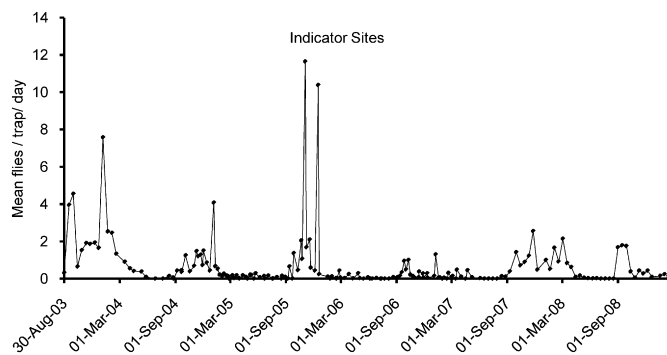


Fig. 4. Fruit fly catches from the cue-lure traps set up at the indicator sites outside the areas of fruit fly treated orchards and towns from June 2003 to February 2009.

Dacus aequalis Coquillett, *D. newmani* (Perkins), *B. chorista* (May) and *B. quadrata* (May) accounted for 3.6%, 1.1%, 0.8%, 0.2% and 0.2%, respectively.

3.3. Effect of AWM on host infestation

A total of 1201 samples of backyard fruit from the town areas of Gayndah and Mundubbera were assessed during the period from 2003 to 2007. The numbers of the collected fruit samples and the overall percentages of fruit fly infestation in different years are shown in Table 2. Fruit fly infestation in backyard fruit was reduced from 60.8% in the samples collected during the period from late 2002 to early 2003 to 45.7% during the period from July to December 2003. Overall, fruit fly infestation in the backyard fruit of the town areas was reduced to approximately 20% by 2004 and remained at this level in 2005, 2006 and early 2007. On average, 21.8% of the total fruit samples collected from the two town areas from July 2003 to February 2007 were found to be infested by fruit flies (Table 3). The implementation of AWM resulted in an overall reduction of 64% in fruit fly infestation in backyard fruit, compared to the data obtained prior to the commencement of the AWM program.

Overall, 99.2% of the 262 infested fruit samples were due to *B. tryoni* with or without small numbers of other pest fruit fly species (e.g. *B. jarvisi* in 3.4% of samples, *B. neohumeralis* in 22.9% of samples). The island fly (*Dirioxa pornia*), which is generally only found in over-ripe or damaged fruit, was reared from 1.9% of samples. From the 18,444 fruit fly pupae recovered from these infested fruit, 1359 parasitoids emerged, representing 7.4% parasitism of fruit fly immatures. Three species of fruit fly parasitoids, i.e. *Diachasmimorpha kraussi* (Fullaway) *Diachasmimorpha tryoni* (Cameron), and *Fopius arisanus* (Sonan), were identified.

3.4. Grower feedback and economic analysis

The general suppression of fruit fly activity in the Central Burnett district and the resultant reduction in fruit infestation were well appreciated by commercial growers in the district. The program evaluation survey showed 96% of growers experienced improved fruit fly control under AWM: no additional insecticide sprays required to protect highly susceptible varieties (e.g. late season Murcott mandarins); extension of the Murcott season into October without fruit fly problems; achievement of improved fruit fly control in table grapes. Furthermore, 100% of respondents recommended that the AWM program continue beyond the trial stage. As a result, an industry funded program “Area-wide management of fruit fly – Central Burnett Phase 2” commenced in June 2007 and continued as an ongoing AWM program.

The benefit cost analysis has shown the net present value of the AWM program and the ongoing industry funded Phase 2 program over the next 10 years will be AU\$5.2 million. The internal rate of

Table 2

Fruit fly infestation in the fruit samples collected from the town areas of Gayndah and Mundubbera prior to and during the area-wide management (AWM) program.

Year	Total samples collected	Number of infested samples	% of samples infested
2002–2003 (prior to AWM)	92	56	60.8
2003–start AWM (Jul–Dec)	70	32	45.7
2004 (Jan–Dec)	395	81	20.5
2005 (Jan–Dec)	403	87	21.6
2006 (Jan–Dec)	260	46	17.7
2007 (Jan–Apr)	73	16	21.9

Table 3

Assessment for fruit fly infestation in fruit samples collected from the town areas of Gayndah and Mundubbera between July 2003 and February 2007.

Fruit name	No. of samples	Number infested
Apple (<i>Malus sylvestris</i>)	7	4
Brazilian cherry (<i>Eugenia uniflora</i>)	12	10
Bush lemon (<i>Citrus jambhiri</i>)	21	5
Calomondin (<i>Citrus mitis</i>)	2	0
Canistel (<i>Pouteria campechiana</i>)	7	3
Carambola (<i>Averrhoa carambola</i>)	21	0
Cherry guava (<i>Psidium cattleianum</i>)	28	23
Crows apple (<i>Owenia venosa</i>)	1	1
Custard apple (<i>Annona squamosa</i>)	4	2
Edible fig (<i>Ficus carica</i>)	11	0
Feijoa (<i>Feijoa sellowiana</i>)	1	1
Grape (<i>Vitis vinifera</i>)	3	0
Grapefruit (<i>Citrus paradisi</i>)	49	8
Guava (<i>Psidium guajava</i>)	16	7
Jaboticaba (<i>Myrciaria cauliflora</i>)	1	0
Kumquat (<i>Fortunella japonica</i>)	24	2
Lemon (<i>Citrus limon</i>)	150	8
Lemonade fruit (<i>Citrus</i> sp.)	2	0
Lime (<i>Citrus aurantifolia</i>)	28	2
Lion fruit (<i>Carissa macrocarpa</i>)	3	1
Litchi (<i>Litchi chinensis</i>)	4	0
Loquat (<i>Eriobotrya japonica</i>)	45	23
Mandarin (<i>Citrus reticulata</i>)	276	26
Mango (<i>Mangifera indica</i>)	53	17
Mulberry (<i>Morus nigra</i>)	59	54
Nectarine (<i>Prunus persica</i> var. <i>nucipersica</i>)	8	6
Orange (<i>Citrus sinensis</i>)	227	26
Passionfruit (<i>Passiflora edulis</i>)	1	0
Pawpaw (<i>Carica papaya</i>)	2	0
Peach (<i>Prunus persica</i>)	32	15
Pear (<i>Pyrus communis</i>)	3	3
Persimmon (<i>Diospyros kaki</i>)	53	4
Plum (<i>Prunus domestica</i>)	2	2
Pomegranate (<i>Punica granatum</i>)	24	1
Pomelo (<i>Citrus maxima</i>)	1	0
Quince (<i>Cydonia oblonga</i>)	18	8
Tomato (<i>Solanum lycopersicum</i> var. <i>lycopersicum</i>)	2	0
Total number of samples	1201	
Number of infested samples	262	
% infestation of samples	21.8	

return is estimated to be 18% and the benefit cost ratio is 2.27:1. This analysis was based solely on the benefits that AWM would generate in alternative systems approach market access protocols if dimethoate is banned for postharvest treatments. The potential benefits from the program should be substantially greater than this if the overall value of the program to all stakeholders is calculated. This economic analysis provides useful information on the potential economic value of implementing similar AWM programs in other horticultural industries and production areas in Australia.

4. Discussion

4.1. Effectiveness of AWM in fruit fly control

Fruit fly control in the Central Burnett district had been an important component of an IPM system for several decades. In the IPM system, weekly protein baiting for fruit flies from January to September was implemented in most citrus orchards while natural and augmented populations of beneficial insects were used to control other insect pests (Smith et al., 1997). Approximately 90% of growers followed the recommended practices, employing local crop consultants to provide pest monitoring services. However, this orchard-by-orchard IPM approach was often insufficient for the control of pest fruit flies because of their dispersal capacity and the

proximity of many untreated hosts in adjacent town areas. It is known that adults of *B. tryoni* can disperse up to 94 km of their own accord (MacFarlane et al., 1987), enabling them to expand the distribution range and to colonise new habitats (Weldon and Meats, 2007; Meats and Edgerton, 2008). Research data showed that in the Central Burnett district fruit flies bred and maintained their populations in untreated fruit even during winter. Furthermore, the abundance and variety of backyard fruiting trees in the town areas of Gayndah and Mundubbera provided “breeding hot spots” for fruit flies in spring and summer (Lloyd et al., 2000). Thus, the high mobility of the fruit fly species can severely compromise the effectiveness of the uncoordinated orchard-by-orchard control efforts (Lewis et al., 1997), requiring curative or therapeutic back-up measures, including chemical sprays with dimethoate in both citrus and non-citrus orchards.

Although the orchard-by-orchard IPM practices had been implemented in the Central Burnett district for more than 20 years (Smith et al., 1997) before the AWM program commenced, the male trap catches showed the continuous presence of abundant fruit fly populations in spring/summer seasons and surveys showed the occurrence of high infestation in the untreated fruit across the entire district. The daily catches were up to 240 flies per male lure trap at the time of peak fruit fly activities. The 4-year AWM program reduced the daily catches to 13 or less flies/trap, and thus achieved an overall reduction of 95% in fruit fly activity during the spring/summer peak period with a subsequent overall reduction of 64% in the fruit fly infestation of non-commercial host fruit. In spite of this, it should be noted that the AWM strategies did not consistently reduce infestation in highly preferred backyard hosts fruiting in summer (loquats, mulberries, cherry guava). Fortunately, there were relatively small numbers of these hosts in the Central Burnett district and few wild hosts in the treatment area, which might have facilitated the successful implementation of the AWM program. The overall results suggest that a coordinated approach to the area-wide management of fruit flies is effective in reducing pest pressure in a major horticultural production area where fruit flies are endemic. A more intensive treatment program in town backyards could further reduce fruit infestation and thereby lower seasonal pest populations, but this would be an additional cost to be met in the ongoing industry funded program.

In the AWM system, MAT was applied as a treatment measure, along with protein bait spray and orchard hygiene. MAT is known to reduce male fruit fly populations to such a low level that female mating is disrupted, which in time leads to reduction in pest pressure. Therefore, MAT has been widely used as a mass trapping method in the area-wide suppression of populations in different pest species of fruit flies as well as other insects (El-Sayed et al., 2006). For example, since it was first applied successfully for the control of the oriental fruit fly on Rota Island in 1963 (Steiner et al., 1965), the male annihilation method was used alone or in combination with other control measures for the eradication or population suppression of different species of tephritid fruit flies under different circumstances (Koyama et al., 1984; Stonehouse et al., 2007; Orankanok et al., 2007; Vargas et al., 2008; Huang et al., 2008). In particular, the MAT used in the Central Burnett district was based on the distribution of carriers dosed with cue-lure and malathion insecticide. *Bactrocera tryoni* and *B. neohumeralis* constitute 92% and 5% of the total fruit fly trap catches in the area, respectively (Lloyd et al., 2000). Both of these species respond to cue-lure and hence MAT based on this attractant was effective for trapping and killing males in both pest species. As an additional orchard control, MAT involved minimal cost and labour since it did not require frequent application, was not disruptive to the existing IPM system, and had no adverse crop effects (e.g. phytotoxicity and fruit residues). Because of its low environmental impact,

community acceptance, and ease of application and withdrawal (if required), the MAT was found to be an appropriate and cost effective additional treatment for orchards and town areas in the Central Burnett district.

4.2. Industry and community engagement

The successful implementation of the AWM program in the Central Burnett district was attributable to the high level of industry and community engagement in addition to targeted strategies based on an in-depth knowledge of the pest situation in the treatment area. Almost all citrus growers in the district implemented protein baiting and MAT in their orchards. Many of the growers with large grape plantings also grew citrus, and these growers also implemented the recommended control measures in their orchards. In the town areas of Gayndah and Mundubbera, 89% (624 out of 699) of property owners also engaged in some program activity on their properties. Sixty three percent (441 out of 699) of the property owners agreed to undertake protein baiting or MAT on backyard fruit trees, and the remainder allowed trapping and/or fruit collection in their properties.

The scale of industry engagement was due to the involvement of local crop consultants who collectively serviced approximately 90% of citrus growers in the district, while the generally high level of support from the Central Burnett community resulted from extensive promotional activities. The adoption of an identifiable name and logo (Fruit Fly Force) assisted in attracting the attention of the general public and enhanced community ownership of the program. Displays organised by the research team at local shows and at the biennial Gayndah Orange Festival were particularly worthwhile in promoting and explaining the value of the program to the entire district. Presentations by the research team and consultants and feedback from the CBAWMC representatives ensured that the local government authorities were well informed of the program progress. All communication strategies were positively perceived by the community. Town residents were very supportive to the implementation of town activities during the program and were satisfied with the reduction of fruit fly infestation in their backyard fruits.

4.3. Market access implications

Bactrocera tryoni is a very serious insect pest of a wide variety of fruit and vegetable crops wherever it is endemic in Australia. If fruit flies are not controlled, potential losses could reach AU\$100 million per year, most being attributable to *B. tryoni* (<http://www.agric.wa.gov.au>). In addition to direct damage to the host fruit caused by female oviposition and larval feeding, quarantine restrictions imposed on domestic and international trade can either curtail the entry of fruit commodities from endemic areas to potential export markets, or force the producer to carry out expensive disinfestation treatments (Heather et al., 2002; Follett and Neven, 2006). An alternative to the current heavy reliance on both preharvest and postharvest dimethoate treatments for domestic and export trade is urgently required given the likely restrictions on the use of this chemical in the near future. The fact that the dimethoate alternative domestic protocol ICA-28 for Central Burnett citrus has been utilised since 1999 with no fruit fly detections in certified fruit demonstrates the value of high levels of field control in meeting market access requirements.

The AWM system initiated in 2004 has significantly enhanced this previous on-farm control, thus providing an additional layer of phytosanitary security for all fruit fly host commodities from the Central Burnett district to access both domestic and international markets. Since the implementation of AWM, ICA-28 for citrus has

been approved for market access to fruit fly free areas in NSW. It is hoped that the ongoing AWM program may lead to the wider acceptance of ICA-28 for citrus and to the development of similar market access protocols for other commodities in other areas based on combinations of crop specific natural and applied risk reduction measures.

This AWM system could also be used as a component in a systems approach to achieving quarantine security to expand international markets for the Central Burnett citrus. Ongoing trapping and other monitoring requirements may need to be modified to meet specific trading partner's requirements but the extensive pest and crop related data which has already been generated provide a sound basis for the possibility of establishing and maintaining an Area of Low Pest Prevalence as defined in the International Standards for Phytosanitary Measures (i.e. ISPM No. 30). Such alternative market access pathways will be particularly critical for maintaining domestic and international markets if dimethoate postharvest treatments are restricted in the near future and alternative treatments (e.g. 16 day cold) are not practical or economically feasible for some markets.

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