An Example of How Chemical Regulation is Affecting Biosecurity Policy-Making: Mediterranean Fruit Fly in Western Australia

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Abstract

The principal chemicals used by Western Australia's horticultural industries for field control and post-harvest disinfestation procedures for Mediterranean fruit fly are soon to be withdrawn from use due to public health concerns. When this occurs, the necessary switch to alternative control methods such as bait sprays and intensive fruit fly trapping will involve additional producer costs. Given these costs, this paper evaluates the option of eradicating Mediterranean fruit fly from the State and discusses possible cost sharing arrangements between government and industry that could be reached for mutual benefit.

Keywords:
Biosecurity; Mediterranean fruit fly; pest management

Introduction

Of the 80 or so fruit fly species native to Australia, only a select few have emerged as prominent pest species (Horticultural Policy Council 1991). One is an introduced species, the Mediterranean fruit fly (*Ceratitis capitata* [Wiedmemann]), or Medfly, which has been established in the State of Western Australia (WA) for more than 100 years. This insect affects most commercial fruit crops and over 60 native fruit species (Hooper and Bateman 1982; Hooper and Drew 1989). Females inject eggs below the skin of host fruit where they hatch and the larvae feed on the pulp (Christenson and Foote 1960; Botha and Hardie 2000).

WA is the only Australian State where Medfly is established[1]. The pre- and post-harvest disinfestation procedures required throughout most of the State's horticultural production areas are estimated to cost producers around $10.2 million per annum (Cook 2012). However, future restrictions on organophosphorus insecticide use are set to increase this figure. Dimethoate and fenthion are broad-spectrum organophosphorus insecticides used to control a range of pests insects in commercial and backyard host plants, including fruit flies. These chemicals are applied as cover sprays on susceptible fruit trees, with some of the chemical penetrating fruit where it kills fruit fly eggs and larvae (Horticultural Policy Council 1991).

The Australian Pesticides and Veterinary Medicines Authority (APVMA) has recently conducted a dietary risk assessment following a recommended revision of the Acceptable Daily Intake (ADI) of dimethoate by the Office of Chemical Safety (APVMA 2010). The revision recommended lowering the ADI from 0.02 mg/kg/day to 0.001 mg/kg/day (APVMA 2010). The subsequent APVMA risk assessment called for restrictions on the application of this chemical to the surface of edible fruit (APVMA 2011). A similar review is currently being carried out for fenthion in response to concerns over environmental impacts of orchard use and is also expected to result in severe restrictions for use in commercial fruit crops (Mengersen et al. 2012). The implications for fruit-fly control methods in Australia are profound. Indeed, a State and Federal intergovernmental working group, the Domestic Quarantine and Market Access Working Group, is currently developing a national response plan to help affected industries to deal with the likely outcomes of both APVMA reviews. This is likely to comprise recommendations for coordinated regional approaches to fruit fly control using baiting and trapping techniques.

The financial impact that the removal of dimethoate and fenthion is likely to have on fruit fly susceptible industries might increase the appeal of eradication as a policy option for Medfly management. While it has been investigated in the past, excessive costs have formed a barrier for WA biosecurity policy makers. In 2001, Mumford et al. (2001) estimated the relative costs of investing in an eradication program for Medfly using the Sterile Insect Technique (SIT). Their study assumed that eradication would involve a phased program over six years requiring the release of approximately 100 million sterile male flies per week. The annualised cost of implementing an eradication programme (in current value terms) was estimated to be $15.7 million and the likelihood of success was concluded to be high given several important factors favouring WA's situation[2].

In this paper, we explore the potential benefits of Medfly eradication as a policy alternative to on-going control. Firstly, we determine if eradication represents a lower cost option than ongoing control using baiting and trapping in the wake of the ban on organophosphate chemicals. We do so using a bioeconomic model to quantify the likely difference in Medfly costs over time under an eradication and a baiting and trapping scenario. This difference is then integrated with the Mumford et al. (2001) estimate of the annualised cost of implementing an eradication programme to predict whether there will be a net positive or negative effect on the State from choosing eradication over control. We then discuss possible public and private cost sharing arrangements for future Medfly policy that will have a beneficial effect on net social welfare as the chemical ban takes effect in WA.

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[1] In the early part of the twentieth century it was also present in New South Wales, but was displaced by Qfly and is now known not to occur (Horticultural Policy Council 1991).

[2] These include: (i) SIT being a well established technology; (ii) the phased program could move from less climatically suited areas of the State into the Perth region, leaving smaller infestations in the north until last; and (iii) a relatively small area of infestation needs to be treated relative to similar eradication programs elsewhere in the world (Mumford, Knight et al. 2001).

Methods

In this section we determine if the annual Medfly costs under an eradication strategy are greater or less than estimated impacts under a baiting and trapping strategy.   We do so by comparing two cost streams over time; one estimating the costs of horticultural production with Medfly in the system in time period one and the second without Medfly in time period one. The difference between these two cost streams provides an estimate of the annual costs imposed on the State's economy from Medfly control rather than its eradication. Moreover, this result represents the breakeven level of investment for implementing an eradication programme. That is, if eradication can be achieved at a lower cost, a net benefit is likely to result. If not, eradication is likely to generate a net loss for the WA economy.

We assume that the current presence of Medfly is eliminated from host industries and concentrate on events that might subsequently transpire. Rather than estimate the likely costs of eradicating the current Medfly population, as Mumford et al. (2001) did, we compare the costs to host industries of maintaining Medfly area freedom to those currently incurred as a result of Medfly's presence. So, we are effectively comparing the difference in host industry costs without (i.e. *eradication*, where the current Medfly population is removed) and with (i.e. control using *baiting and trapping*, where Medfly remains present for the foreseeable future) the pest. As such, we treat the protection of Medfly area freedom and eradication of future incursions in host growing areas as an on-going alternative to a baiting and trapping approach with respect to Medfly management. The area and annual gross value of production for host industries are given in Table 1.

TABLE 1 NEAR HERE

Let us assume that WA Medfly host industries are represented by a single planning body or cooperative group which determines the appropriate biosecurity strategies. Predicted investment paths are defined as a function of expected yield and input cost changes (and hence profitability) from investing in Medfly eradication and exclusion relative to on-going control using a baiting and trapping approach. The planning body will choose to invest in Medfly eradication and exclusion over on-going control in production region *i* in time step (i.e. year) *t* if it is expected to reduce grower losses by a greater amount than the associated difference in costs. The dichotomous adoption variable, α_t, which takes on the value of one if the central planner invests in eradication across *n* regions in year *t* and zero otherwise, is defined as:

$$\alpha_t = \left\{ \begin{matrix} 1 \text{ if } \sum_{i=1}^{n} d_{it} \geq \sum_{i=1}^{n} c_{it} \\ 0 \text{ if } \sum_{i=1}^{n} d_{it} < \sum_{i=1}^{n} c_{it} \end{matrix} \right\} \qquad (1)$$

where d_{it} is the total difference in predicted cost increments induced by Medfly between maintaining the eradication and baiting and trapping policy options in region *i* in time *t*, and c_{it} is the annualised cost of implementing an eradication programme in region *i* in time *t*. We focus on the estimation of $\sum_{i=1}^{n} d_{it}$ to compare it to the estimate of $\sum_{i=1}^{n} c_{it}$ put forward in

Mumford et al. (2001) (i.e. a current value of $15.7 million per annum). This is the threshold value of $\sum_{i=1}^{n} d_{it}$ before α_t assumes a value of zero.

We assume that under the Medfly eradication scenario pre-border measures currently in place to protect WA agriculture from other fruit fly species will also be effective in maintaining area freedom from Medfly post-eradication[3]. Post-border biosecurity measures that would be employed if eradication was achieved include monitoring through pest surveillance, robust detection and rapid response to incursions. If, as a result of these measures, a Medfly incursion in a commercial host production area is detected early enough, there may be a strong likelihood of local eradication through host removal and destruction. Hence, the value of d_{it} in equation (1) is influenced by local eradication costs and probability of eradication success. This probability of success is assumed to decline negative exponentially at a rate of $e^{-0.15A_{it}}$, where A_{it} is the area infected with Medfly in fruit growing region *i* in year *t* weighted by the probability of incursion and density of infestation. If an outbreak is not detected early enough, a longer term management strategy is required to minimise Medfly impacts over time using baiting and trapping methods.

Algebraically, we can express d_{it} as:

$$d_{it} = \begin{cases} E_{it}A_{it} \text{ if } A_{it} \leq A_{it}^{\text{erad}} \\ Y_{it}P_tA_{it} + V_{it}A_{it} \text{ if } A_{it} > A_{it}^{\text{erad}} \end{cases} \qquad (2)$$

where: E_{it} is the cost of eradication per hectare in region *i* in year *t*; A_{it} , as stated above, is the area infected with Medfly in region *i* year *t* weighted by the probability of an outbreak and population density; A_{it}^{erad} is the maximum technically feasible area of eradication in region *i* in year *t*; Y_{it} is the mean change in yield resulting from Medfly despite pre-harvest treatments in region *i* in year *t*; P_t is the prevailing domestic price for hosts in year *t*; and V_{it} is the increase in variable cost of production per hectare from pre- and post-harvest treatments in region *i* in year *t*.

Post-eradication, Medfly arrival events in fruit growing areas are generated using unrestricted entry and establishment probabilities (denoted z^{ent} and z^{est}, respectively), stated in Biosecurity Australia (2008). A Markov chain process, described in Hinchy and Fisher (1991), is used to change z^{ent} and z^{est} over time according to a vector of transitional probabilities. These transitional probabilities describe the likelihood of moving from one pest state to another. z^{ent} and z^{est} are combined to form a probability of invasion for a specific fruit-growing region *i*, z_i :

$$z_i = z^{\text{ent}} \times z^{\text{est}} \text{ where } 0 < z_i < 1 \qquad (3)$$

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[3] Exotic fruit flies of economic importance to WA include various species from the *Bactrocera, Dacus* and *Ceratitis* genuses. Species of concern include *B. aberrans, B. bancroftii, B. batemani, B. brunnea,* Solanum fruit fly (*B. cacuminata*), *B. chorista,* Oriental fruit fly (*B. dorsalis*), *B. endiandrae,* Halfordia fruit fly (*B. halfordiae*), *B. mayi,* Banana fly (*B. musae*), *B. mutabilis,* lesser Queensland fruit fly (*B. neohumeralis*), *B. nigra, B. pulchra, B. strigata,* Queensland fruit fly (*B. tryoni*), *Dacus absonifacies, D. aequalis* and *D. signatifrons,* Natal fruit fly (*Ceratitis rosa*). Phytosanitary measures are imposed on host commodities imported from interstate and international destinations areas where these species are established Western Australian (Western Australian Quarantine and Inspection Service 2009). While they lower the probability of fruit flies entering WA, they also raise the landed price of non-domestic fruit.

To describe A_{it}, Medfly re-entry and movement post-establishment in multiple regions are estimated using a stratified diffusion model combining both short and long distance dispersal processes. Parameter estimates for this model appear in Table 2, and are explained below[4].

TABLE 2 NEAR HERE.

The model is derived from the reaction diffusion models originally developed by Fisher (1937) which have been shown to provide a reasonable approximation of the spread of a diverse range of organisms (Dwyer 1992; Holmes 1993; McCann *et al.* 2000; Okubo and Levin 2002; Cook *et al.* 2011; Cook *et al.* 2012). These models assert that an invasion diffusing from a point source will eventually reach a constant asymptotic radial spread rate of $2\sqrt{r_i D_{ij}}$ in all directions, where r_i describes a growth factor for Medfly per year in region *i* (assumed constant over all affected sites) and D_{ij} is a diffusion coefficient for an affected site *j* in region *i* (assumed constant over time) (Hengeveld 1989; Lewis 1997; Shigesada and Kawasaki 1997; Cook, Carrasco et al. 2011; Cook, Liu et al. 2012).

Hence, assume that the first of a probable series of sites, *j*, to re-establish in WA occupies a homogenous environment in region *i* and expands by a diffusive process such that area populated at time *t*, a_{ijt}, can be predicted by:

$$a_{ijt} = z_i\left[\pi\left(2t\sqrt{r_i D_{ij}}\right)^2\right] = z_i\left(4D_{ij}\pi r_i t^2\right). \tag{4}$$

By assuming D_{ij} is constant across all sites *j*, demographic stochasticity (and consequent non-uniform invasion) is ignored.

The density of Medfly within a_{ijt} influences the control measures required to counter the effects of the infestation, and thus partially determines the value of A_{it}. Assume that in each site *j* in region *i* affected, the population density, N_{ijt}, grows over time period *t* following a logistic growth curve until the carrying capacity of the host environment, K_{ij}, is reached:

$$N_{ijt} = \frac{K_{ij} N_{ij}^{\min} e^{r_i t}}{K_{ij} + N_{ij}^{\min}(e^{r_i t} - 1)}. \tag{5}$$

Here, $N_{ij}^{\min}$ is the size of the original population at site *j* in region *i* and r_i is the intrinsic rate of density increase in region *i* (assumed to be the same as the intrinsic rate of population increase) (Cook *et al.* 2011; Cook, Liu et al. 2012).

In addition to a_{ijt} and N_{ijt}, the size of A_{it} depends on the number of nascent foci or *satellite* population sites in year *t*, s_{it}, which can take on a maximum value of $s_i^{\max}$ in any year (Moody and Mack 1988). These sites result from events external to the initial outbreak itself, such as weather phenomena or human activities, which periodically jump the expanding

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[4] Note that due to the uncertainty surrounding some of these parameters, they are specified using a range of distributional forms, rather than point estimates. Types of distributions used in the table and elsewhere in this report include: (a) pert – a type of beta distribution specified using minimum, most likely (or skewness) and maximum values; (b) uniform – a rectangular distribution bounded by minimum and maximum values; (c) binomial – returning a zero (failure) or one (success) based on a number of trials and the probability of a success; (d) discrete - a distribution in which several discrete outcomes and their probabilities of occurrence are specified; (e) Poisson - a discrete distribution returning only integer values greater than or equal to zero with a specified mean value.

population beyond the invasion front (Cook, Fraser et al. 2011; Cook, Liu et al. 2012). A logistic equation is used to generate changes in s_{it} as an outbreak continues:

$$s_{it} = \frac{s_i^{\max} s_i^{\min} e^{\mu_i t}}{s_i^{\max} + s_i^{\min}(e^{\mu_i t} - 1)} \tag{6}$$

where μ_i is the intrinsic rate of new foci generation in region *i* (assumed constant over time) and $s_i^{\min}$ is the minimum number of satellite sites generated in region *i*.

Given equations (4)-(6), A_{it} can be expressed as:

$$A_{it} = \sum_{j=1}^{m} \left(a_{ijt} N_{ijt}\right)^{s_{it}} \text{ where } 0 \le A_{it} \le A_i^{\max} . \tag{7}$$

In terms of preventing Medfly re-establishment and naturalisation in WA, eradication is the only government incursion response activity simulated in the model. We do not consider other policies such as slow-the-spread (Sharoy *et al.* 1998; Tobin and Blackburn 2007). We assume that eradication is immediately attempted once susceptible industries and government have been alerted to a Medfly outbreak. The detection that triggers the response is, on average, assumed to occur in 60 per cent of incursion events simulated by the model using a binomial distribution (i.e. binomial(1.0,0.6)). As stated previously, the probability that the eradication attempt will successfully remove the incursion is arbitrarily assumed to decline negative exponentially at an average rate of $e^{-0.15A_{it}}$ (see Table 2). If this does not occur before the population has spread to a pre-defined threshold area, A^{erad}, which is assumed to be between 300 and 500 hectares, the eradication attempt is aborted.

If detection does occur sufficiently early, eradication involves the application of chemical thinning agents to remove fruit from affected trees and the creation of intensive buffer zones (using the same thinning methods) around affected sites. These buffer zones are circular with a diameter of 10 hectares. Fruit is subsequently removed from all treated orchard floors and buried.

Although when detection does not occur early in an outbreak or when an eradication attempt fails to prevent an incursion from reaching A^{erad}, eradication is aborted, this does not mean that Medfly then spreads unimpeded within the virtual world of the model. This is because, as stated previously, it is assumed baiting and trapping schemes will be put in place and adjusted according to the needs of host industries. However, this will add to annual costs as the frequency of these activities will increase and are not guaranteed to be 100 per cent effective. Yield losses despite the control are estimated to average around 3.5 per cent per annum (represented in the model as Pert(2.0,3.5,5.0)) (Cook 2012).

The spread of Medfly is connected dynamically with the costs of eradication and on-farm control simply by multiplying the area infested by a constant marginal damage cost (or an average damage cost). For outbreaks involving less than A^{erad}, area is multiplied by thinning costs (see notes below Table 2). When the population spreads beyond A^{erad} the remaining area is multiplied by an average on-farm insect management costs.

Given equations (6) and (7), the total benefit to the central planner of adopting an eradication policy for Medfly in year *t*, $\mathrm{B}_t^{\mathrm{P}}$, can be expressed as:

$$\mathrm{B}_t^{\mathrm{P}} = \sum_{i=1}^{n} d_{it} \alpha . \tag{8}$$

In the following section we report estimates of $\sum_{i=1}^{n} d_{it}$ over a 20-year period. In this context, recall that eradication is not worthwhile (i.e. $\alpha = 0$) if $\sum_{i=1}^{n} d_{it} < \sum_{i=1}^{n} c_{it}$, where $\sum_{i=1}^{n} c_{it}$ has been estimated at approximately $15.7 million per annum in current value terms (Mumford, Knight et al. 2001).

Finally in this section, note that despite Medfly eradication from commercial production areas being assumed to have been achieved at the outset of the analysis, our assumptions are such that re-establishment is likely to occur at some point or multiple points over the estimation period. The model simulates these re-establishment events as a Poisson process where Medfly successfully re-establishes in WA on an average of one year in six (see Table 2). Therefore, the resultant expected spread area values under both the eradication and baiting and trapping scenarios are positive.

Where uncertainty surrounds parameter values they are specified within the model as distributions. A Latin hypercube sampling algorithm is then used to sample from each distribution. In each of 10,000 model iterations one value is sampled from the cumulative distribution function so that sampled parameter values are weighted according to their probability of occurrence. The model calculations are then performed using the parameter values and distributions given in Table 2.

Results

The calculations have been aggregated across all production regions of the State over a 20-year time frame to produce Figure 1. The box-whisker plot used in Figure 1 (and Figure 2) shows the 25th percentile, the mean, the 75th percentile and remaining values up to and including the 5th and 95th percentiles. The boundaries of the boxes (shaded grey) indicate the 25th percentiles and the 75th percentiles and the lines extending from the top and bottom of each box indicate values between the 5th and 25th percentiles and between the 75th and 95th percentiles.

FIGURE 1 NEAR HERE.

The corresponding producer losses induced by Medfly populations over time are shown in Figure 2. All projected benefits are discounted at five per cent per annum. The difference between these cost streams in each time step represents $\sum_{i=1}^{n} d_{it}$. The large amount of uncertainty in predicted damage under the eradication scenario is immediately apparent, and is to be expected given the element of risk involved in re-establishment, detection and response.

FIGURE 2 NEAR HERE.

If we summarise each cost flow as an annual average present value, a baiting and trapping approach is expected to cost the State approximately $26.4 million per year, while eradication is expected to involve costs of around \$6.6 million per year. Hence, the net benefit to the central planner over time of adopting eradication over control using a baiting and trapping strategy averages \$19.8 million per year (i.e. $\sum_{i=1}^{n} d_{it} = \$1.98 \times 10^7$). Recall from equation (1), this represents the threshold level of $\sum_{i=1}^{n} c_{it}$ beyond which the central planning body will choose not to invest in an eradication as an alternative to a baiting and trapping strategy (i.e. $\alpha_t = 0$). The standard deviation of the distribution of average annual eradication net benefits is \$7.5 million and skewness -1.3 (i.e. the distribution is skewed left).

Since the annualised cost estimate of Mumford et al. (2001) of implementing an eradication programme is \$15.7 million in current value terms, our results indicate that the net returns to the industry of eradication would be positive. More specifically, given our estimate of $\sum_{i=1}^{n} d_{it}$, this analysis implies a rough benefit cost ratio of 1.3:1.0[5].

Discussion

When compared to baiting and trapping over the course of a season, cover spraying with organophosphates is a relatively cheap fruit fly control option. But, given that these chemicals are no longer available to fruit producers because of public and environmental health concerns, the issue now is to determine what the next best management alternative is and what proportion of management costs should be borne by industry and the public.

If producer cost is the sole determining factor, our results show that eradication represents a superior biosecurity policy option when compared to baiting and trapping. If we add the \$15.7 million annualised cost of achieving eradication (i.e. Mumford et al. (2001)) with the expected losses of \$6.6 million due to incursions, the eradication policy option carries an overall cost of \$22.3 million per annum. On paper, an industry contribution of around \$10.2 million per annum to this eradication policy option would see them no worse off than they were prior to the APVMA review of organophosphate chemicals (i.e. Cook (2012)). The remaining \$12.1 million then represents the required public contribution based on the human health and environmental benefits (from reduced chemical usage) received.

The reality of organising industry contributions is likely to be more complex. Because Medfly has such a wide host range there are many different industries who stand to benefit from eradication. If eradication is successfully achieved, there are also a large number of industries to be monitored for breeches of biosecurity protocols and possible Medfly reintroductions. So, even if a group of ten or so primary host industries were to organise themselves into a cooperative to eradicate Medfly, they could not prevent other non-contributing industries from benefiting from the maintenance of State area freedom. Moreover, they would be unable to prevent non-contributors from adopting poor biosecurity risk management practices that jeopardise Medfly area freedom. This non-exclusivity problem reduces incentives to contribute to the cooperative good.

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[5] Note that with current host industry gross production values, our estimate of $\sum_{i=1}^{n} d_{it}$ is equivalent to a yield increase of almost 10 per cent per year across all affected fruit crops.

A partial solution might lie in fostering networks of self-monitoring ‘elements’ capable of rapid detection within particular sub-divisions of an industry or growing region. Grower groups in which decisions are made collectively house incentive structures for reporting since the group as a whole potentially share the burden of Medfly control. In WA, component enterprises of an industry or group of industries can be separated by large distances. They can also be characterised by different cost structures and have different capacities to absorb the effects of invasive species introductions (Cook and Fraser 2002). Hence, cooperative formation may be advised on a regional or sub-regional level rather than a State level to minimise transaction costs.

State legislation, specifically the *Agricultural Produce Commission Act 1988* (WA), enables the formation of Producer Committees to oversee activities deemed by the Agricultural Produce Commission to be in the interests of a gazetted agricultural industry. Activities can be funded through the imposition of a fee for service on Members of the industry affected, including producers, wholesalers, exporters and retailers (Section 16). Producer Committees determine the size of a fee for service imposed upon their constituency, and the funds collected are held in the State Treasury to be drawn upon as needed.

To date, the legislation has not been used to secure funds that might be used for eradication, although it has been used in the provision of community baiting schemes in some shires for Medfly. But, there is nothing in the Act itself which would preclude such actions being undertaken in future. Having been sourced directly from the private beneficiaries of eradication, a precautionary pool of resources would avoid bureaucratic delays and reduce time lags (King and Pitchford 2001).

However, this is only an advantage when the funds are used for activities that are desirable to a majority of industries represented by a Producer Committee. Preferences of cooperative members may vary sharply across regions, and measures may be required to guard against situations where a distribution of expected on-farm impacts is ‘skewed’ (Hart and Moore 1996). Stakeholder diversity within cooperatives may lead to differing opinions regarding appropriate uses for collective funds in relation to Medfly, and where this is severe the optimal level of decision-making bodies must be flexible (Gatzweiler 2005).

Conclusions

In this paper we have shown that restrictions on organophosphorus insecticide use in WA are set to increase the costs of managing Medfly to the extent that maintaining eradication becomes the least-cost biosecurity policy option compared to on-going control using baiting and trapping. Specifically, with net benefits from maintaining eradication estimated to be $19.8 million per year compared with the estimated annualised (current value) cost of implementing an eradication programme of $15.7 million (based on Mumford et al. (2001)), this suggests a net benefit will be generated for the State from implementing eradication as its biosecurity policy option. Moreover, if collective horticultural industries were to contribute approximately half the costs of eradication their financial position would be similar to what it was prior to the chemical use restrictions. However, due to the diversity of industries potentially benefiting from Medfly eradication it may be difficult to form cooperative arrangements and establish appropriate cost contributions.

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Table 1. WA Medfly host industry area and production value information, 2012

Host	Area (ha) [a]	Gross value of production ($ million) [a]
Capsicum	186	9.2
Citrus	1 436	25.7
Mango	840	12.5
Pome fruit	1 400	50.0
Stone fruit	600	52.6
Table grapes	238	26.1
Tomatoes	393	29.7

[a] ABS (2011) and Ghose et al. (2011).

Table 2. Parameter values.

Description	Values
Probability of Medfly re-entry and establishment under an eradication scenario. [a]	Uniform(0.7, 1.0)
Detection probability.	Binomial(1.0,0.6)
Population diffusion coefficient (m^2/yr). [b]	Pert(5.0×10^5,6.0×10^5,7.0×10^5)
Minimum area affected immediately upon entry (m^2).	1.0×10^3
Maximum area affected (m^2). [c]	4.9×10^7
Intrinsic rate of population and density increase (yr^{-1}). [b]	Pert(0.20,0.35,0.50)
Minimum population density (#/m^2).	1.0×10^{-4}
Maximum population density (#/m^2). [b]	Pert(100,550,1000)
Minimum number of satellite sites generated in a single time step (#).	0
Maximum number of satellite sites generated in a single time step (#). [b]	Pert(50,60,70)
Intrinsic rate of new foci generation per unit area of infestation (#/m^2). [b]	Pert(1.0×10^{-2},3.0×10^{-2},5.0×10^{-2})
Discount rate (%).	5
Supply elasticity. [d]	Uniform(0.2,0.8)
Demand elasticity. [d]	Uniform(-1.1,-1.0)
Fall in domestic price of susceptible fruit following loss of area freedom status and relaxation of trade restrictions (%). [e]	Pert(10,15,20)
Maximum area considered for eradication (ha). [e]	Pert(300,400,500)
Cost of eradication ($/ha). [f]	Pert(2.0×10^4,3.0×10^4,4.0×10^4)
Negative exponential rate of decline for eradication success probability with respect to area affected. [e]	Pert(-0.20,-0.15,-0.10)
Pre-harvest baiting and trapping costs if eradication fails ($/ha). [g]	Pert(50,100,150)
Post-harvest treatment costs if eradication fails ($/ha). [i]	Pert(1.0×10^3,1.3×10^3,1.6×10^3)
Yield reduction despite control if eradication fails (%). [a]	Pert(2.0,3.5,5.0)

[a] Cook (2012); [b] Specified with reference to Waage et al. (2005); [c] ABS (2011) and Ghose (Ghose, Poole et al. 2011), inclusive of citrus fruit, pome fruit, stone fruit, mango and table grapes. This is the area currently affected by Medfly. Note 1ha = 10 000m^2; [d] Ulubasoglu et al. (2011); [e] Cook (2012); [f] Assumes average density of planting of 600 trees/ha and fruit thinning, raking, transport and destruction costs amounting to around $20 per tree. This is inclusive of chemical costs for 2 applications of a thinning agent, represented here using the desiccant ammonium thiosulphate applied in a concentration of 65-100ml/100L (approximately 1.2L/ha, or $40/ha), and application costs of $50/ha. Post-thinning raking and disposal costs consist of labour (team of three at $50/hr each) and front-end loader ($100/hr) hire for approximately 4 hours per hectare. Assume that in addition to the removal of fruit from an area where fruit flies have been detected, a buffer zone approximately 10 hectares in diameter around the site is created (Cook 2012). These costings do not include supplementary hand thinning or baiting and trapping costs associated with demonstrating the reattainment of area freedom. They also ignore the possibility that older trees will be removed by orchardists rather than thinned; [g] Costs comprise of $2/ha bait spray costs and $50/ha labour cost per application. Applications will vary according to seasonal variability and weathering of bait sprays, but are likely to take place at weekly intervals during the growing season (although in the case of stone and pome fruits this may increase to twice-weekly applications when fruit are full sized). Assume the number of applications is between 20 and 40 (i.e. discrete({20,25,30,35,40}, {1,1,1,1,1})) per growing season. Further assume that bait sprays are used in conjunction with a Male Annihilation Technique (MAT). This employs an intensive network of traps to attract and kill male flies (Cunningham 1989; Katsoyannos *et al.* 1999). Traps and exposed wicks are deployed at a density of 10-20/ha in susceptible fruit orchards (i.e. discrete({10,12,14,16,18,20},{1,1,1,1,1,1}) at a cost of $10-15 per trap (assume Lynfield traps (Dominiak and Nicol 2010)); [i] Cold disinfestation of fruit is estimated at $50-100/tonne (Florec *et al.* 2010; White *et al.* 2011). No market opportunity costs have been included here, but we note that they may be a concern for growers with lengthy delays of around two weeks to complete cold storage treatments (De Lima *et al.* 2007).

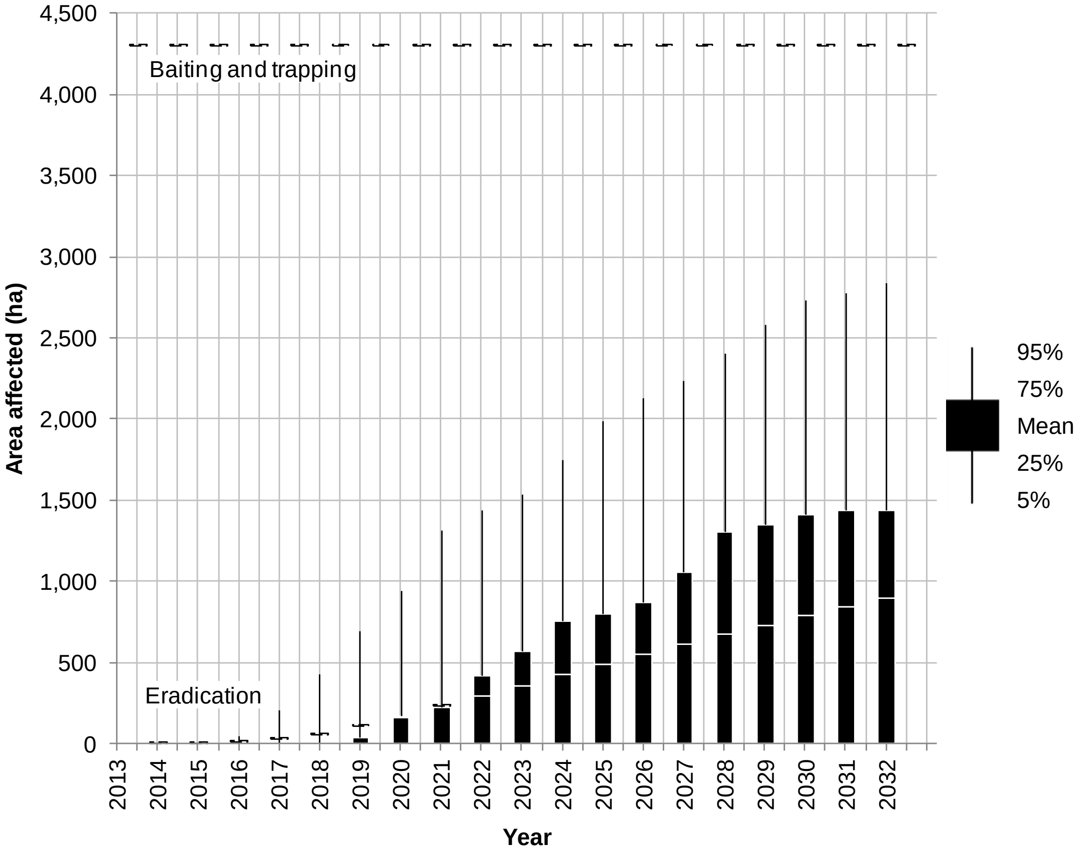

Figure 1. Likely spread of Medfly over time under baiting and trapping and eradication policies.

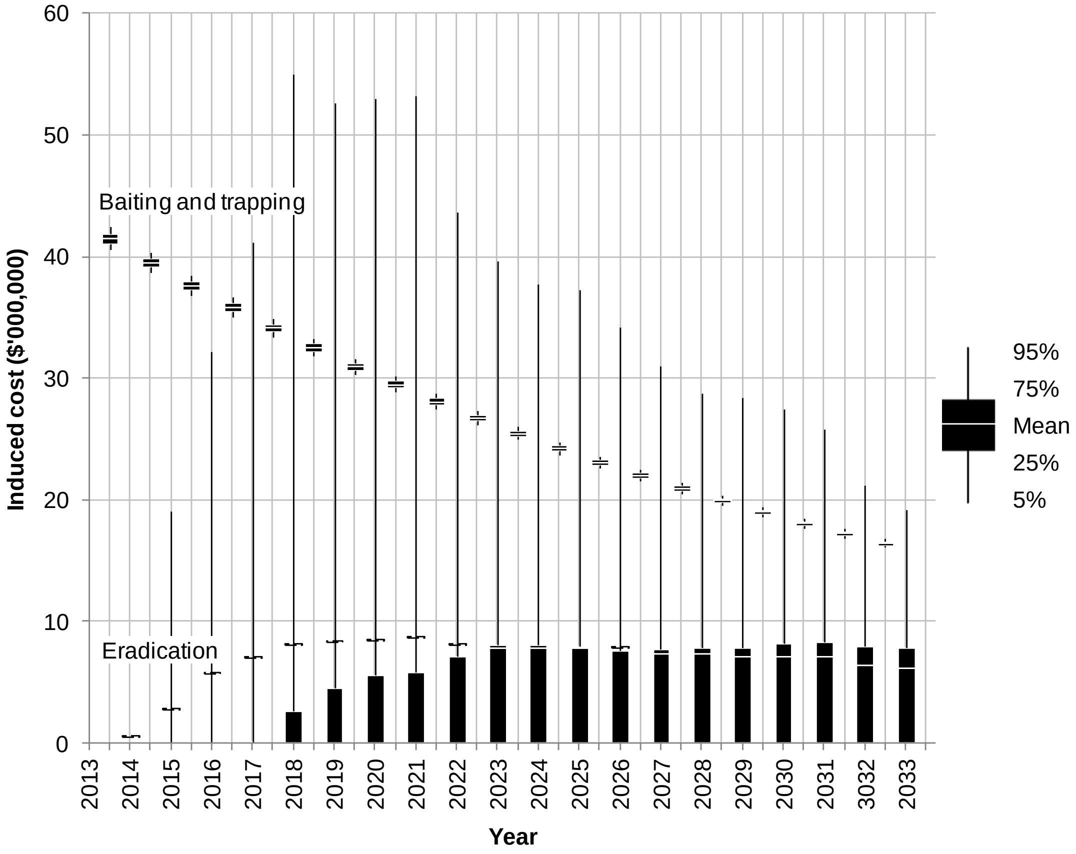

Figure 2. Predicted cost increments induced by Medfly in the eradication and baiting and trapping policy options.