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Optimal Investment in R&D for Plant Biosecurity

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Executive Summary

The operation of export supply chains for agricultural and horticultural produce depends on compliance with the biosecurity standards set for export markets. This project uses a systems based approach to analyse the optimal economic design of biosecurity management strategies based on biophysical, economic and market regulation factors (such as ISPM 26).

The project analysed two contrasting export orientated biosecurity systems: ***Area Wide Management (AWM) for the Queensland fruit fly (Qfly, Bactrocera tryoni); and Network Wide Management (NWM) of stored grain insects.*** Both AWM and NWM entail the provision of a 'biosecurity' public good to producers through surveillance, border protection and eradication. The biosecurity manager's problem is one of information gathering and action in a system where firms and the general public do not always have an incentive to contribute optimally to the biosecurity public good. Thus the system either depends on government intervention (AWM) or commercial, monitoring and prophylactic eradication (NWM). A detailed bioeconomic model has been built for each system (Q-FAWM for Qfly AWM and GRANEWM for stored grain biosecurity) and the main results are presented below.

Area Wide Management (AWM) for Qfly: the Sunraysia Pest Free Area (PFA) for Qfly, bordering Victoria and NSW, is an AWM scheme for Qfly. The AWM scheme includes surveillance, border protection and eradication to ensure that high value produce can be exported to sensitive markets. The key benefits of market access are the cost savings from avoiding post-harvest treatments of citrus and table grape crops. Furthermore, the Sunraysia PFA is embedded within the larger Fruit Fly Exclusion Zone (FFEZ) where both eradication and post-harvest treatments are undertaken, thereby acting as a buffer to the dispersal of Qfly from Australia's east coast into the PFA.
Q-FAWM, the Sunraysia AWM model, is based on the observed landscape ecology of Qfly within the FFEZ. The parameters are derived from the NSW PestMon database, which is related to both GIS and climate databases. The novel aspect of this research is that we provide an economic framework that links science on the landscape ecology of the Qfly to decision making. Previous Benefit-Cost analyses of Qfly AWM for the Sunraysia pest free area have measured aggregate costs and benefits for the whole PFA or FFEZ. The manager has little evidence from this analysis of how the policy can be optimally adjusted, in terms of surveillance intensity, area designated or eradication resources. The AWM model developed here allows for the analysis of marginal changes in the design of the pest management system and consequent benefits.

For example, we estimate the annual total potential benefits from AWM in the Sunraysia pest free area at $39.3 million. The annual variable costs of surveillance for the Q-FAWM model were $0.8 million, for eradication $0.8 million, and for post-harvest of $5.4 million. The majority of post-harvest costs are incurred in the Mildura region where production value is greatest and also where the potential benefits of AWM are highest. However, post-harvest costs may vary significantly: between $1 million and $23 million per year on average over a 20 year period. In some high value regions, such as in and around Mildura, it would be economic to increase trapping density so as to reduce the

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initial size of a population at the declaration of an outbreak, following the population's arrival and subsequent detection, and so improve the likelihood of population eradication. In regions of low production value and low outbreak probability it is economic to reduce trapping effort.

The area wide manager has to justify spending public and producer funds and also has to provide scientific justification for changes in market access policy. Ideally, public agencies would vary their management to optimise the benefits realised by an AWM scheme by tailoring the scheme to local conditions. This modelling approach may start to provide managers with the evidence required, especially as more data becomes available from the ongoing monitoring of the trapping grid. Eventually this evidence may be accepted as a basis to modify market access rules.

Network Wide Management (NWM) of stored grain**:** Grain biosecurity shares some common elements with AWM, but also possesses many differences. The stored grain pests are largely endogenous to the network, as opposed to Qfly where outbreaks occur sporadically due to external invasions. Biosecurity starts on farm where farm storage is a potential source of infestation and the development of insect resistance to phosphine. At farm and at receival sites biosecurity management depends upon capital invested in grain storage and transport network.

The attributes of the biosecurity system suggest a four module spatial and temporal bioeconomic model, GRANEWM. The first module is a ***biosecurity contract*** (based on BetterFarm IQ) between the bulk handler and the farmer that ensures an optimal level of biosecurity effort by the farmer; the second ***farm to receival*** module represents optimal farm delivery to receival sites; and the third ***receival to port*** module represents a least cost (transport and biosecurity cost) choice for delivering wheat to Kwinana. Finally, the ***biosecurity risk*** module which calculates the probability of infested grain delivered by farmers propagating through the grain storage and transport network to infest grain at the port.

In the Kwinana zone there are around 6000 crop farms. Each farm is spatially located with an estimate of their wheat production, based on shire yield estimates. The ***farm to receival*** module estimates the choice of farmers to deliver to one of 114 receival sites based on the costs of delivery as a function of road distance. The farm is also able to select one of three delivery periods based on expected prices and farm storage capacity. The total grain produced based on the 2008/2009 season was 4.55 million tonnes, worth around $1.37 billion. The farm storage available is estimated to be around 0.9 million tonnes, around 20 per cent of the crop. This implies that stored grain biosecurity largely falls on CBH, but there is a significant and growing element that depends on farm decision making. In this the ***biosecurity contract*** is critical as it provides an incentive for farmers to engage in biosecurity measures such as fumigation of on-farm sealed storage in return for a price premium. This model shows that farmers only engage in effort if there is effective monitoring at receival sites and an adequate price premium for clean grain. The effectiveness of farm storage management could be improved by a system of certification whereby farmers demonstrate that stores are sealed and suitable for phosphine fumigation. The ***receival to port*** model is a representation of transport, storage and biosecurity costs associated with moving grain from 114 receival sites to

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Kwinana in an insect free state. The model represents the infrastructure available at each receival site and the likely effectiveness of each storage type in terms of ensuring effective fumigation.

Biosecurity, even in the presence of phosphine resistant stored grain pests, depends on the availability of sealed storage where grain can be treated to minimise the risk of infestation. The implication is that resistance increases the value of sealed vertical storage and reduces the value of unsealed stores.

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1. Aims and objectives

Original aims and objective

The original research proposal identified the following aims and objectives:

Project aim: The aim of this project is to develop common methods to appraise investments in biosecurity R&D. The methods developed will be applied to two contrasting systems; the first will consider the establishment and maintenance of fruit fly area freedom through surveillance and control. The second will consider methods of maintaining biosecurity in stored grain through managing resistance to a range of insecticides and designing surveillance systems to support market access.

Project objectives: Develop methods for the integrated assessment of R&D investment to safeguard biosecurity within pest management systems and develop market access for area freedom and stored grain.

Project outcomes

Research: Improved methods of biosecurity assessment that allow for uncertainty, time and multiple strategies.
Industry: Improved outcomes from biosecurity research investment decisions. Measured in terms of increased producer profitability or increased net benefits to society.

Revised aims and objectives

The aims and objectives of the project were modified as it became apparent that the data on the area wide management problem was not available in an accessible form and models of the biophysical system for Qfly and grain biosecurity were not readily available for the study areas. Thus a different set of objectives were developed, however, they will still allow for an assessment of the final project outcome. Thus the revised objectives are:

- Develop representative disaggregated models of the pest management systems including biophysical links, management and economics.
- Analyse the optimal design in term of surveillance, eradication and post harvest treatment of the pest management system given current technology.
- Provide an estimate of the likely industry gains due to new technology in surveillance, eradication and post-harvest treatment.

The project outcome 'Improved methods of biosecurity assessment that allow for uncertainty, time and multiple strategies' has been achieved. The project has also developed new methods for benefit cost analysis for biosecurity systems. In particular for the AWM and NWM systems the disaggregated approach to benefit cost analysis allows an analysis of value for components of the system. This includes, for instance, varying surveillance intensity for Qfly and closing selected grain stores to manage biosecurity.

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2. Key Findings

Area and Network Wide Management

Two neighbours may agree to drain a meadow, which they possess in common; because 'tis easy for them to know each other's mind; and each must perceive, that the immediate consequence of his failing in his part, is, the abandoning the whole project. But 'tis very difficult, and indeed impossible, that a thousand persons shou'd agree in any such action; it being difficult for them to concert so complicated a design, and still more difficult for them to execute it; while each seeks a pretext to free himself of the trouble and expence, and wou'd lay the whole burden on others.

David Hume, A Treatise on Human Nature, 1739

Globally, the development of world trade and expansion of the intercontinental movement of people and goods has raised concerns about threats to agriculture and natural environments from invasive organisms (Lichtenberg and Lynch, 2006; Mumford, 2002; Olson and Roy, 2002). Moreover, food safety standards have low tolerances for pesticide residues in food. As the number of markets demanding low pesticide and low pest commodities grows (Hendrichs *et al.,* 2005; Mumford, 2005), Australian horticultural producers need to apply pest management methods that satisfy both food safety standards and invasive species protection requirements, particularly in those horticultural industries that depend heavily on exports to pest-free markets. One possible alternative is area wide management (AWM) where a pest is managed at regional scales through an integrated strategy that can include: border control; surveillance; eradication; pre- and post-harvest treatments; education; market regulation; trade agreements and/or, a long term administrative structure. Network wide management (NWM) differs only in the topology of the landscape it deals with, where in place of a contiguous landscape under area wide management the landscape is mapped as a network of 'nodes' and 'links'. These nodes and links mirror the transport of a pest through transport and storage networks such as rail or shipping. NWM is treated here as a special case of AWM.

The key argument underpinning AWM of insect pests is that "a number of serious economic pests can be effectively managed using an organised and coordinated attack on their population over large areas rather than by using a field–by–field approach" (Koul et al, 2008, p.1). Indeed, the uncoordinated effort of individual producers and households is generally insufficient for the effective management of highly mobile pests (Klassen, 2005). Although AWM programmes may vary in their application with location and the pest targeted, the implementation principles are fundamentally similar; a number of control measures are uniformly applied over a large area to reduce the population of the pest targeted to predetermined levels (Faust, 2008; Devorshak,

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2007).[1] For instance, AWM of fruit flies commonly involves the deployment and monitoring of traps over large areas, control of the movement of host produce, eradication of outbreaks and use of the sterile insect technique.

AWM has often been implemented for the management of fruit flies (Lloyd et al., 2010), perhaps more frequently than is generally recognised (Mumford, 2000), and its role in agricultural trade is expected to become increasingly important (Devorshak, 2007). While there are numerous studies on the AWM concept, the principles of AWM implementation, and its current applications in Australia and worldwide,[2] detailed economic analyses of AWM are rare. Without economic analysis, it is difficult to assess the social value of different management strategies and technologies, methods and scale of operations of an AWM programme. As government budgets tighten generally, technical managers of AWM face growing pressures to economize and to provide evidence that the costs of their operations are justified by the benefits. There is then a need for further economic analysis of AWM and its tools to devise AWM programmes that optimally allocate resources and to make informed, evidence-based judgements about trade-offs between available options. Sound analyses of the costs and benefits of AWM programmes are needed to decide how to best proceed before the programme is implemented, or to suggest operational improvements after an AWM programme has been established (Mumford, 2005).

In common with many other pest management problems, AWM is concerned with the provision of a public good where producers who do not contribute to the programme cannot be prevented, at a reasonable cost, from reaping the benefits of AWM (Burnett, 2006; Hennessy, 2008; Hinchy and Fisher, 1991). Moreover, if the execution of AWM is left to the uncoordinated efforts of producers there is a risk that some producers might contribute less expecting that others will provide sufficient levels of protection (free rider problem) (Perrings et al., 2002). Therefore AWM programmes have to be provided by a State or National government regulator. The regulator's problem is one of determining the most efficient management policy and devising it so that resources are efficiently allocated across the different technologies available for prevention, surveillance and control of the pest targeted.

The State or National government regulator also faces the 'weakest/weaker link' problem, the risk of policy failure in 'letting one through'. For instance, if one roadblock is not effective in an AWM programme and fails to keep the pest out of the area, the fact that all others may be effective is irrelevant. This is a common issue in pest management: hence some authors have modelled the prevention of invasive species as

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1 International standards have been developed to provide guidelines for the implementation of control measures. Some of these standards have direct implications for AWM, such as the International Standards for Phytosanitary Measures (IPSM 26, 2006; IPSM 30, 2008).

[2] See for instance Koul et al. (2008) and the different volumes from the joint FAO/IAEA international conferences on area-wide control of insect pests; Tan (2000) and Vreysen et al. (2007) for a review of the historical foundations of AWM and its current applications. For fruit flies see Hendrichs et al. (2007) and Klassen (2005) for a review of the concept of AWM and the use of the sterile insect technique in AWM programmes; Lloyd et al. (2010) for an account of the implementation of AWM in the Central Burnett District of Queensland; and Jessup et al. (2007) for a description of the AWM tools used in Australia.

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a public good of the 'weakest link' type reflecting the situation where the overall level of prevention depends on the capacity of the weakest contributor (Horan et al., 2002; Perrings, 2001; Perrings et al., 2002; Shogren, 2000). However, this would imply that zero prevention by one contributor always causes the overall level of prevention to be zero effective. Since this is generally not the case, Burnett (2006) expressed the problem as of a 'weaker link' type to better illustrate the situation where lower investments in prevention and control by some contributors may reduce the returns of those that invest more. Burnett (2006) demonstrate that the incentive structure that results from the weaker link public good problem causes contributors to inadequately invest in invasive species management (individual contributors might invest less expecting that others will provide sufficient levels of protection), reinforcing the need for careful design of pest management policies and effective resource allocation.

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Area Wide Management of Queensland Fruit Fly

This case study presents a bioeconomic analysis of the measures undertaken in surveillance, eradication and post-harvest treatment that underpin The Greater Sunraysia Pest Free Area (GSPFA) biosecurity system. Established in 1996, the GSPFA region covers approximately 2.5 million hectares across northern Victoria, western New South Wales and eastern South Australia (Figure 1). The two key control zones are the Sunraysia PFA, including the high value production areas of Mildura and Swan Hill, embedded within the Fruit Fly Exclusion Zone (FFEZ) covering the NSW Riverina towns of Griffith and Hillston, Echuca and Shepparton in Victoria, and Loxton in South Australia (Figure 1). The main horticultural crops of the Sunraysia PFA are grapes (wine, dried and table) and citrus (table and juiced), and are valued at close to $500 million a year (excluding wine production). In 2006, under new management arrangements, the GSPFA was jointly funded by Victorian and NSW governments and the three key horticultural industries, citrus, summerfruit and table grapes. The revised management methods are consistent with international Standards for Phytosanitary Measures 26 (ISPM, 2006).

A surveillance network of Lynfield traps, spaced every 400m within residential areas and every 1000m in horticultural production areas, is inspected weekly over the entire FFEZ. A 'market rule' agreed to by trading partners requires a Qfly outbreak to be declared once the number of Qfly captured exceeds a threshold amount (generally five male Qfly within two weeks and 1 km), recognising that Qfly populations can often arrive in a local area and then die out due to poor environmental conditions and/or allee effects. At the declaration of an outbreak eradication measures are initially undertaken for 12 weeks over a 1.5 km radius eradication zone. The key difference between management within the FFEZ and the PFA is that post-harvest treatments are required of all produce sourced from the FFEZ. In comparison, post-harvest treatments are not required of produce from the PFA until an outbreak is declared. Simultaneous to eradication measures a suspension zone is declared, the size of which depends on the market, but which is generally 15 km in radius about the origin of the outbreak. All produce within the suspension zone requires post-harvest treatments until a pest free status is reinstated. Market rules defining reinstatement again vary with each market, but predominately follow the 'one generation and 28 days' rule: i.e., a time period equivalent to one generational life cycle and then 28 days must elapse without further incidence of Qfly captures for market reinstatement to occur (the USA citrus market follows a '3 generation' rule). In the advent of new captures the reinstatement rule is reset again to start from day '0'. Thus how long a generation takes to elapse depends on the local and seasonal climate. The length of these generations is calculated through day degree accumulations to which Qfly development is closely coupled (NFFWG, 2008). Hence, the ecology of Qfly directly affects the value of any management strategy, as it is the life cycle of the Qfly that determines not only the period of market loss and consequent value of post-harvest treatments, but also the intensity of monitoring required to detect Qfly populations early to enable more rapid eradication. Climate change, new technological advances in surveillance and control, and changing patterns of human

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assisted dispersal of Qfly (as infested fruit) will all influence economically optimal AWM strategies into the future.

Previous CBA and Reviews of AWM for Qfly in Australia

There have been few analyses on the economics of Qfly management, despite Qfly's status as a major horticultural pest and an extensive biological literature.[3] The economic analyses of Qfly management in Australia are restricted to benefit–cost analyses (BCAs) of one or small handful of discrete management scenarios. The scenarios are delimited in area and do not evaluate the interactions between the technologies used, the area studied, the nature of the pest or the market rules defining when access is permitted to restricted markets. Here we detail the historical development of CBA to support AWM of Qfly in Australia:

Bateman (1991): Following numerous fruit fly outbreaks across Australia this report recommended the establishment of pest free areas in selected high value horticultural regions. Net benefits were estimated to range between $10.1 million and $14.5 million per annum for the Tri-State strategy being implemented, and which defines the FFEZ and Sunraysia PFA across South Australia, Victoria and New South Wales.

PricewaterhouseCoopers (2001): Reported an annual net benefit of $14.9 million (growers and exporters captured most of the benefits) in the Fruit Fly Exclusion Zone (FFEZ) and a benefit cost ratio for the Strategy of 2.5:1. This included improved market access benefits of $9.9 million.

TSFFSSG (2001): Confirmed that continuation of the Tri-State Fruit Fly Exclusion Zone strategy is desirable. Issues of cost sharing between state governments and industry resulted in states largely going their own way in terms of implementing area freedom.

Bull (2004): Examined possible cost sharing arrangements in support of area-wide management of Qfly within NSW.

[3] See Clarke et al. (2011) for a comprehensive review of Qfly ecology.

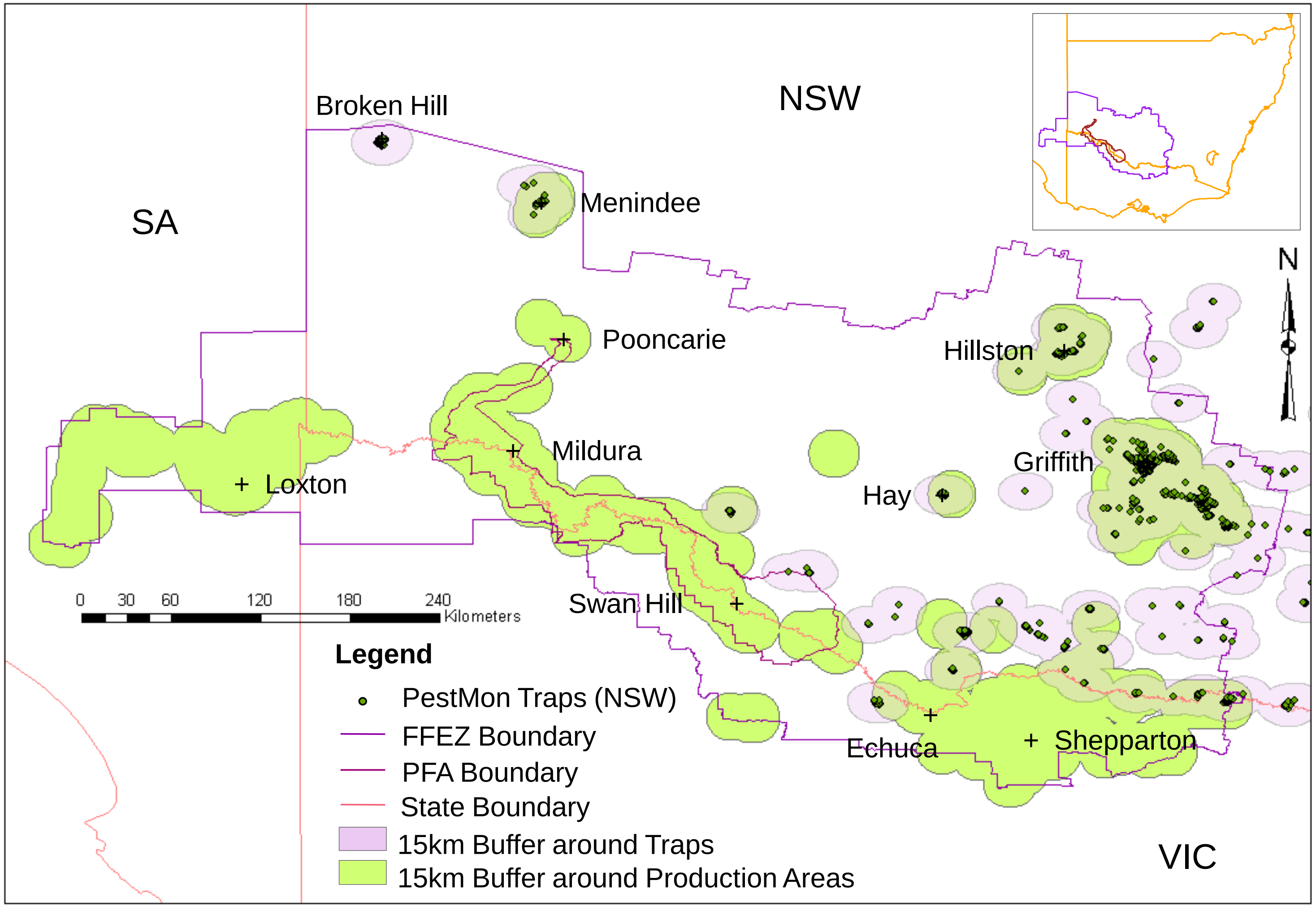

Figure 1. Map of the FFEZ Region in South Eastern Australia

[Land use: Bureau of Rural Services, DAFF; Trap Data: PestMon Database, Industry and Investment NSW; AWM Boundaries: Department of Sustainability and the Environment, Victoria]

Kalang (2008): Suggested three alternative PFA scenarios for the continuance of Victoria's Qfly AWM strategy: (1) establishment and maintenance of specific pest free areas (PFAs); (2) re-establishment of state-wide freedom; and (3) AWM through the establishment of PFAs and areas of low pest prevalence. Areas of Low Pest Prevalence (ALPP) are defined in accordance with ISPM 30 (2008), where a fruit fly pest may occur at low levels subject to effective surveillance, control or eradication (NFFWG 2008).

Franco-Dixon and Chambers (2009): presented a BCA of the AWM of fruit flies project in the Central Burnett District of Queensland prior to the scheme's implementation. The authors considered the probability of the Australian Pesticides and Veterinary Medicines Authority (APVMA) banning the use of dimethoate on fruit and the probability of the Interstate Certification Assurance (ICA-28) scheme being extended to include four Australian States. Franco-Dixon and Chambers (2009) estimated a net present value for the AWM project over ten years of $5.2 million, with a benefit cost ratio of 2.27:1. Significantly, a probability was assigned to different outcomes from market access negotiations both with and without AWM, and used to evaluate expected benefits.

Ha *et al.* (2010): Provides each of the Kalang (2008) scenarios with a BCA. The estimated annual benefits of each of the Kalang (2008) scenarios were virtually equal for the three management options, approximating $33 million. These benefits were comprised of: $6.3 million in market access benefits; pre-harvest chemical costs of $1.4 million; and, avoided post-harvest treatments of $25.6 million. The difference appears in the estimated annual costs, resulting in a benefit cost ratio over twenty years larger for option 3 than for the other management options (option 3 resulted in a benefit cost ratio of 2.35:1 compared with 2.02:1 for option 1 and 2.15:1 for option 2). The Ha *et al.* (2010) report considered ecological risk, insofar as producing Monte Carlo simulations of the observed frequency of outbreaks for each statistical division, while applying a fixed eradication cost to each outbreak.

Access Economics (2010): Building on the Ha *et al.* (2010) BCA the study examined the question of who should pay for maintenance of Victoria's PFAs, and potential mechanisms of cost recovery. Access Economics (2010) recommend a 60:40 to 80:20 split between Victorian commercial fruit growers and the Victorian Government, reflecting principles of both beneficiary pays and risk creator pays. This compares to the 50:50 to 70:30 split recommend by PriceWaterhousecoopers (2001) for the whole of the FFEZ. Two cost recovery mechanisms were suggested, given that maintenance of PFAs requires public agency direction: (1) a regionally specific industry levy where practical; otherwise, (ii) a broader national biosecurity levy.

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Our BCA analysis differs from that of Ha *et al* (2010) in a number of ways:

1. Our analysis of pre-harvest treatment costs both inside and outside the Sunraysia PFA from ABS data suggests that currently pre-harvest treatments are equal between regions. This may reflect a measure of 'insurance' against the risk of an outbreak if pre-harvest controls are relaxed. However, the analysis may also be confounded by the relatively low proportion of stone fruit produced within the PFA (2.9% of total vine and fruit tree horticulture), as *Ha et al.* (2010) consider the avoidance of pre-harvest treatment costs only for stone fruit. We therefore value the potential pre-harvest treatment cost savings at a maximum of $256,000, but this value is excluded from our analysis for simplicity, given its small value and the lack of evidence of savings on pre-harvest treatments in practice.
2. Market access benefits were not calculated here, with Ha *et al.* (2010) estimating these benefits at $6.3 million for citrus exports destined for the USA only. Currently USA regulators are considering allowing chilling as a post-harvest treatment. If this change in the trade rules is successful then this market access benefit will be lost to the PFA, though at the gain of citrus producers elsewhere. Significantly, this is an instance where renegotiation of market access rules can lead to decreased competitive advantage for previously privileged producers. More generally we do not consider the potential gain or loss of markets that may result from a change in the AWM strategy.
3. Our analysis assigns different post-harvest treatments costs to grape and citrus, following consultation with industry. While the post-harvest cost of stone fruit is the same at $50/tonne, grapes are assigned a post-harvest cost of $127/tonne and citrus $93.50/tonne. This inflates the value of post-harvest treatments in our analysis compared to Ha *et al.* (2010).

Consistent with the DPI Victoria analysis consumer benefits, including the reduced use of chemical controls, are ignored as are the benefits of non-commercial horticultural production, and only producer benefits examined. Hence we will focus on post-harvest costs, in addition to eradication and monitoring costs.

The first of two trends to be observed in the history of BCAs and reviews of the tri-state FFEZ strategy is the increased emphasis on state based evaluations of PFA implementations since 2001. The recent Victorian studies have supported a strategy of PFAs in key production areas, excluding residential areas from the PFAs (with incumbent buffer zone) given the greater likelihood of outbreaks in residential areas, and by defining the remainder of the west of the state as an area of low pest prevalence (ALPP). These analyses have excluded NSW from the BCA, though it could be argued that effective management within the NSW FFEZ would positively influence the success of PFA regimes within Victoria. Some of the benefits and costs in maintaining the proposed PFAs are thus misrepresented. The importance of the FFEZ in a BCA of the Sunraysia PFA is accentuated in our study in that we calculate post-harvest costs for all produce from non-PFA production regions, alongside eradication costs for the whole of the FFEZ. Thus the burden of

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the cost of maintaining the Sunraysia PFA falls within the NSW jurisdiction, while a significant share of the benefits are realised within the Victorian jurisdiction. In essence, the cost of maintaining eradication and post-harvest treatment protocols in the non-PFA FFEZ needs to be traded off against the benefits realised within the Sunraysia PFA for a rigorous assessment of the PFA.

The second trend is a move towards a probabilistic representation of the 'risk' of outbreak or policy failure in both Ha *et al.* (2010) and Franco-Dixon and Chambers (2009). The need to provide some measure of policy risk reflects the importance of Qfly ecology to the success of any PFA strategy. Indeed, citing Ha *et al.* (2010), "*the frequency of Queensland fruit fly outbreaks is a key determinant of total eradication and disinfestation costs*". We extend this insight to stating that the climate driven ecology of Qfly also drives the duration of outbreaks, and the probability of an outbreak is dependent on a number of possibly unknown landscape factors (e.g., transport networks, AWM management, and food availability). In fact we move to a temporally and spatially explicit model of both the local probability and the duration of outbreaks.

The above BCAs have shown that ongoing funding of such AWM schemes is justified, but there is little analysis about their design (Florec *et al.*, 2010a). They answer whether continued investment in AWM of fruit flies is justified. These studies do not deal with key questions regarding the structure of the AWM programme itself, such as how much surveillance should be undertaken, how much should be invested in the eradication of outbreaks or how large an area should the PFA cover. Ha *et al.* (2010) analysed the three options proposed in the Kalang (2008) report that included different areas in the AWM programme. However, these authors did not analyse changes in the technologies used, the environmental conditions of the areas studied, the market rules and the availability of produce throughout the year.

In an analysis of the principles and problems of the economics of area–wide pest control, Mumford (2000) discerned four major questions that need to be answered when devising an AWM programme: (i) should the pest be controlled locally or area–wide; (ii) over which area; (iii) what is the most efficient form of control; and (iv) what level of organisation should be used. However, economic studies on Qfly management that explicitly consider these questions are practically non–existent. Economic analyses of other invasive species, although they provide remarkable insights, are not entirely relevant to Qfly management due to differences between species in their ecology.[4] On a more fundamental level previous BCAs of the Tri-State FFEZ strategy represent an aggregated, or

[4] Economic studies of invasive species often present optimisation models that minimise the cost of management, potential damages and the risk of introductions (or maximise the net present value of expected economic benefits associated with the management of a pest). A variety of invaders have been considered in the economic literature: weeds (Cacho et al., 2007; Chalak-Haghighi et al., 2008), insects (Ceddia et al., 2009; Bogich and Shea, 2008), vectors of plant diseases (Brown et al. 2002), plant diseases (Acquaye et al. 2005), fungi, vertebrate animals (Bomford and O'Brien, 1995), etc.

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top-down, approach to estimating the benefits and costs of each strategy. These strategies are specified as discrete scenarios, though Ha *et al.* (2010) do undertake sensitivity analyses of key parameters employed in their BCA model. Evaluation of discrete scenarios is of benefit to policy makers who need to choose one overarching AWM strategy for a region. However, this is not the same decision problem as faced by the AWM manager, who has to decide where to best invest limited public funds among a 'portfolio' of available management options. To this purpose a disaggregated, or 'bottom-up', bioeconomic approach is beneficial, that links an increased investment in individual management options to the key benefit of avoided post-harvest treatment costs.

Linking Investment to Benefits in Surveillance

"We define the art of conjecture, or the stochastic art, as the art of evaluating as exactly as possible the probabilities of things, so that in our judgements and actions we can always base ourselves on what has been found to be the best, the most appropriate, the most certain, the best advised; this is the only object of the wisdom of the philosopher and the prudence of the statesman."

Ars Conjectandi, Jacob Bernoulli, 1713

All the benefit-cost analyses that have been undertaken for the FFEZ and PFA schemes have indicated a significant return on public funds. We take a different approach: instead of measuring the efficiency gains from the whole scheme we develop a bioeconomic model to assess the benefits of marginal changes in the intensity of surveillance. This turns out to be a particularly challenging problem as the effectiveness of the whole PFA management system rests on the ability of the surveillance system to rapidly detect a pest once it has arrived into a local area. For this reason, of all the possible elements of an AWM strategy then the economic benefits of surveillance (i.e., earlier time to detection) is perhaps the most difficult to estimate and link to its costs. For instance, increased investment in eradication leads to more rapid eradication following an outbreak and earlier market access recertification; and an increased investment in border control may lead to a decreased probability of outbreak.

Significantly, a theoretical literature on pest management, often linked to empirical models has started to emerge during the 1990s, for instance (Olson & Roy 2002, 2008). The focus of these studies has been on the invasion of exotic pests rather than repeated invasions of endemic pests, as is the case of Qfly within the FFEZ. The pest is treated as a stock of a 'natural bad' to be analysed in an equivalent way to a natural resource such as a fish stock where eradication is equivalent to harvesting. Population dynamics has been extended to account for population dispersion (see Kot and Schaeffer, 1986 for a review). The economic importance of dispersion is that widely spread, but sparse, pest outbreaks may have a low probability of observation and a relatively high cost of eradication. In contrast, densely populated and confined outbreaks have a relatively high probability of detection and relatively low cost of eradication.

The economics of pest surveillance is a neglected topic and, to our knowledge, the only systematic treatment in relation to a biosecurity problem is that

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presented by Kompas and Che (2009) for Papaya fruit fly invasions. Their model is based on a dynamic, but non-spatial model of population spread associated with a time to detection (Figure 2). The main purpose of surveillance investment is to minimise the time to detection of a previously unobserved pest arrival. When discovered early, infestations are generally of smaller extent and easier to eradicate. Investment in eradication effort can also reduce the time to suppression of the pest. In the case of Qfly, produce grown in the suspension zone has to be treated before being sent to various fruit fly free markets, but only after a pest population has been detected and an outbreak declared. Post–harvest treatments continue until area–freedom can be reinstated following a no–capture period.

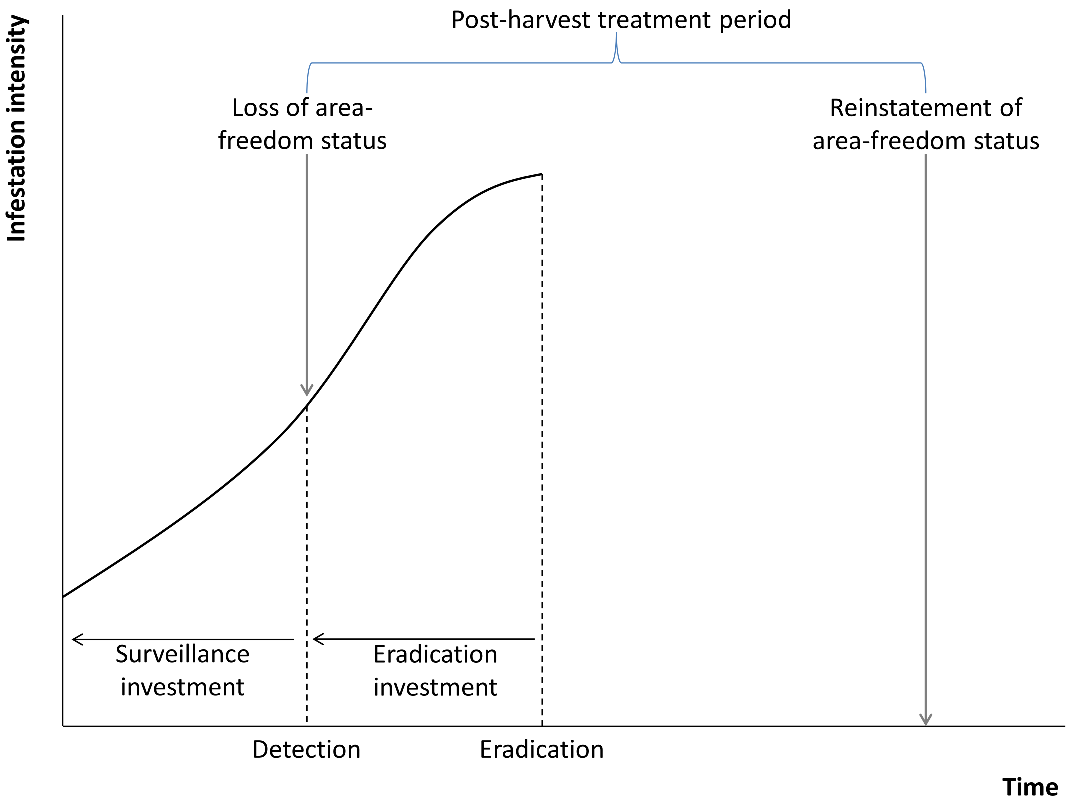

Figure 2. Detection, eradication and reinstatement of area–freedom status following an outbreak (after Kompas and Che, 2008).

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Figure 3. Land Use Data [Source: BRS, 2010]

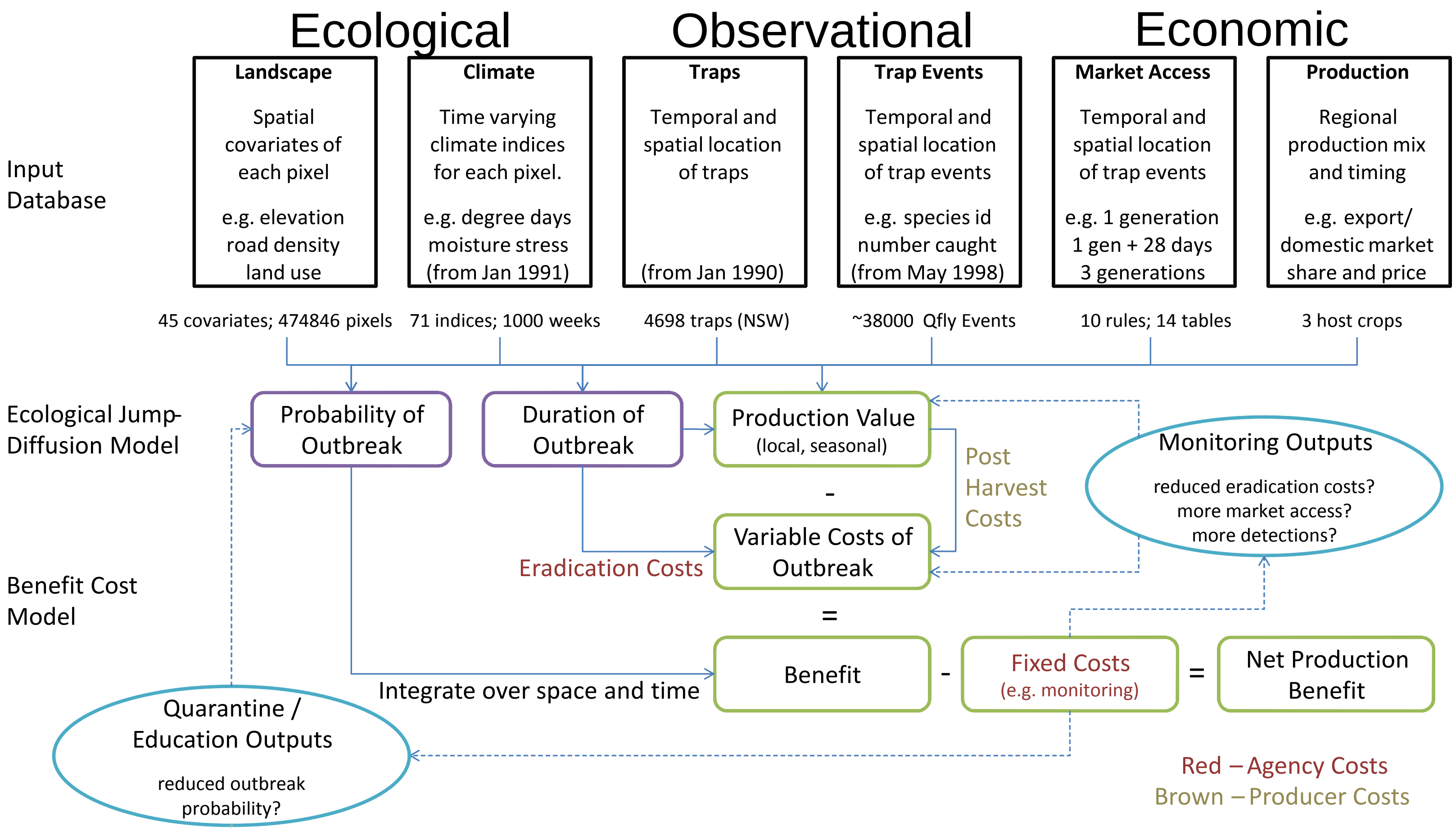

Figure 4. Flow Diagram of BCA Model

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In summary, we have developed an economic framework consisting of a spatially explicit population dispersal model interacting with a defined regime of surveillance over the landscape is given in White *et al.* (2012). Weekly labour and input costs of maintaining surveillance can be evaluated for individual traps and rescaled according to different levels of investment in surveillance, with specific costs for Qfly surveillance within the FFEZ given by Veronique *et al.* (2010b). Calibration of parameters for the hybrid population-surveillance model is given in Sadler *et al.* (2011), with further theoretical development of the model to define a distribution of time-to-detections given in Sadler *et al.* (2012a). In practice, time-to-detections are linked to the distribution of Qfly captures at the declaration of an outbreak. As these 'initial' captures have been observed over the past 14 years of monitoring data, available for the FFEZ, then the distribution of initial captures may be used to predict the duration of outbreaks (i.e., the net period of market access loss), thereby linking investments in surveillance with consequent post-harvest costs (Figure 4).

Data and Model

Definition of Landscape

The FFEZ region was represented as a pixelated landscape with one arcminute resolution (~1.84 km). For each pixel a number of spatial attributes were recorded: road density (m/ha); landuse (5 landuse classes; Figure 3); membership and distance to the PFA and FFEZ management boundaries (km); elevation (m); surface roughness (st. dev. of elevation); distance to coast (km); and number of active Cuelure traps. Temporal covariates recorded on a weekly time step were derived from daily temperature, rainfall and evaporation using the Climex model based on phenological parameters for Qfly (Yonow et al 1998; Sutherst *et al.* 2007). The model is applied to the 886 weeks from January 1994 to December 2010, and considers 5402 pixels where either horticultural production or residential areas are located (Figure 4). Only NSW and Victoria were considered due to the unavailability of both landscape and trapping data for the South Australian Riverlands region of the FFEZ.

Probability of Outbreak

The study utilised the PestMon database held by Industry and Investment, NSW, recording weekly Qfly captures for 1650 permanent and temporary Cuelure traps across the NSW portion of the FFEZ. A market rule of at least five flies trapped within two weeks and 1 km was used to declare 135 outbreaks from June 1998 to December 2010. Calculation of the duration of an outbreak (eradication plus market recertification) required:

1. At least one generation to lapse following the completion of a 12 week eradication period, with no Qfly caught during that time.
2. If Qfly were subsequently caught within 1 km of the outbreak origin then the one generation rule was imposed again when less than five Qfly were caught.
3. If at least five Qfly were trapped then 12 weeks of eradication was imposed again, followed by a reinstatement of one generation rule. For ease of computation the suspension zone was not doubled in size, as required by regulation (Ha *et al*., 2011). However, the duration of the original outbreak was extended by the duration of the subsequent outbreaks.

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The Qfly trapping events were regressed on the spatio-temporal factors using generalised additive models (Wood, 2006). Drought stress, distance from the PFA boundary (Figure 5), and density of roads and residential areas were found to be the key drivers of the probability of captures (Figure 6). A relative risk of outbreaks to capture events was derived from the data and then used to compute outbreak occurrence during simulation runs over the entire FFEZ. Further issues related to inference of the probability of outbreak model are given in Sadler et al. (2012b).

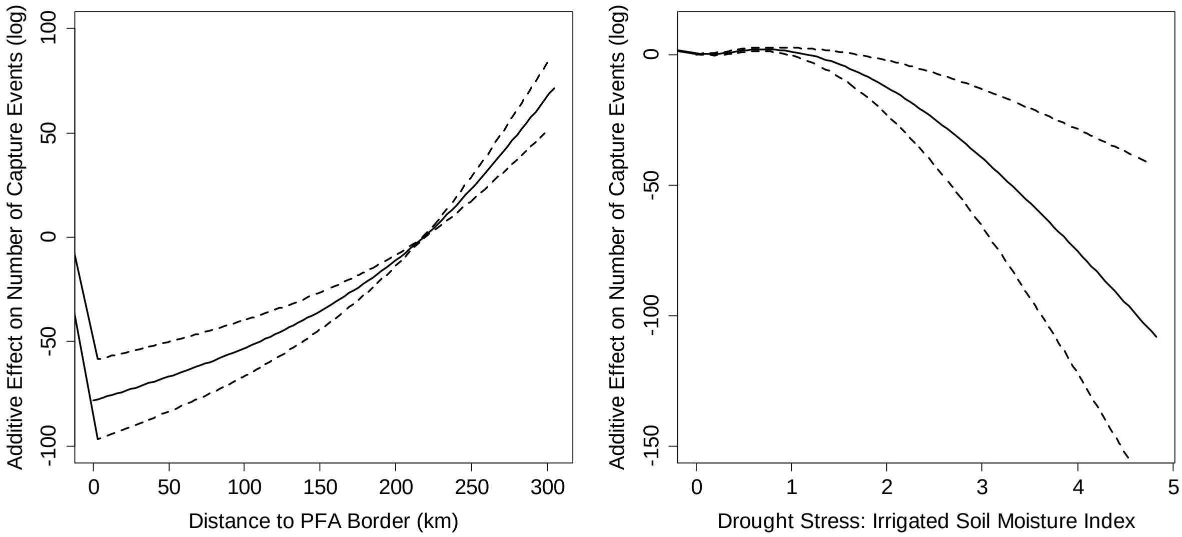

Figure 5. Drought Stress and Management Zone Effects on the Probability of Qfly Captures

Cost of Eradication

The cost of eradication is a function of the duration of the outbreak, with outbreaks of longer duration more likely to require multiple eradication efforts. A single eradication effort was estimated to cost $120,546 (2010 value), and considered the cost of labour, chemical usage, and of sterile insect technology (SIT) releases following the initial two week period of chemical application (Florec *et al.* 2012). Our Qfly model fixes the eradication period at 12 weeks for all outbreaks, in common with eradication practice on the ground, regardless of monitoring effort (Figure 2). What varies in the model are the number of eradication efforts required during any recertification period, where further eradication efforts are undertaken whenever a declaration of outbreak is again triggered within an existing outbreak's 15 km suspension zone. The number of eradications is then taken as an empirically derived stochastic function of outbreak duration (Figure 8). Note that outbreak duration is itself a stochastic function of the initial population captured at the time of detection, with the eradication cost incurred solely at the spatial epicentre of the declared outbreak (Figures 2 and 3). Hence, the total cost of eradication is an indirect function of monitoring effort. Moreover, the number of outbreaks observed correlates with the level of surveillance in the probability of outbreak model (Figure 6), independent of outbreak duration, with marginally more outbreaks detected with increasing trap density in the probability of outbreak model.

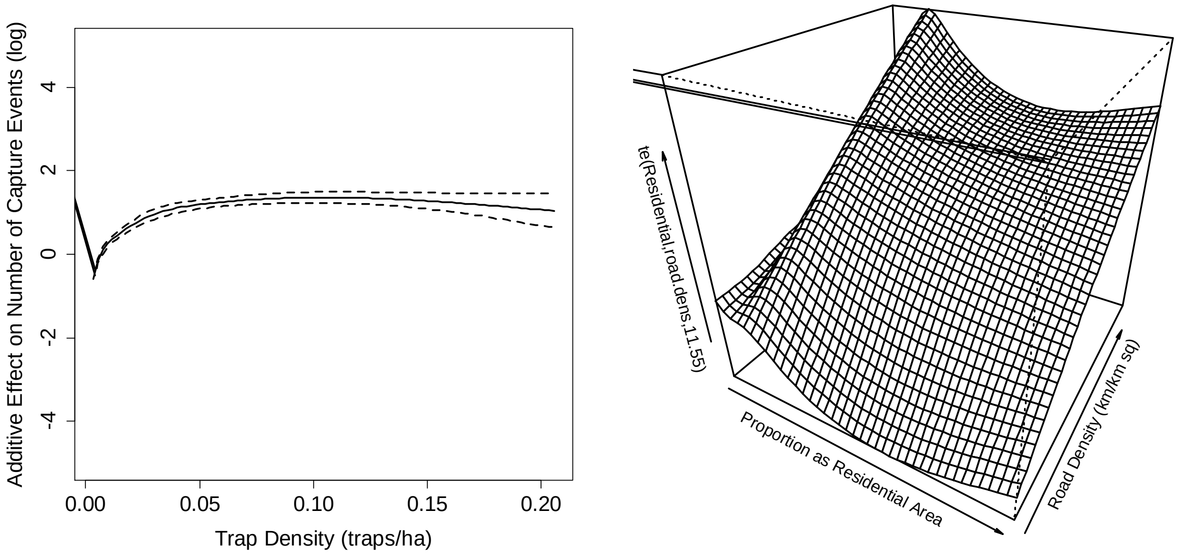

Figure 6. Trap Density, Residential Area and Road Density Effects on Probability of Qfly Captures

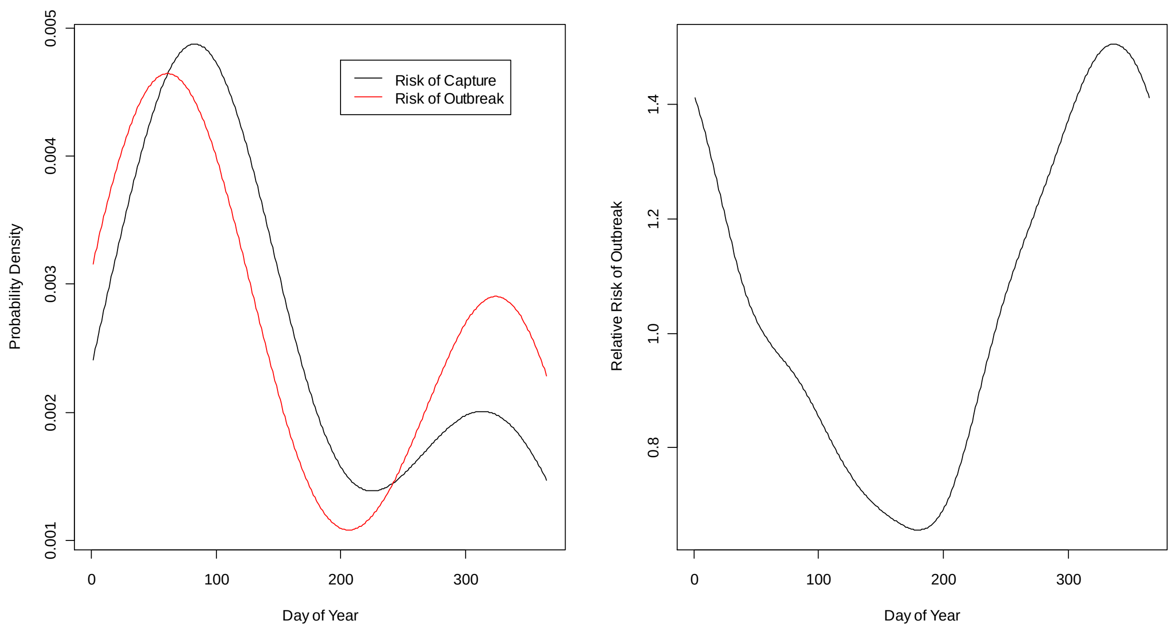

Figure 7. Relative Risk of Outbreak

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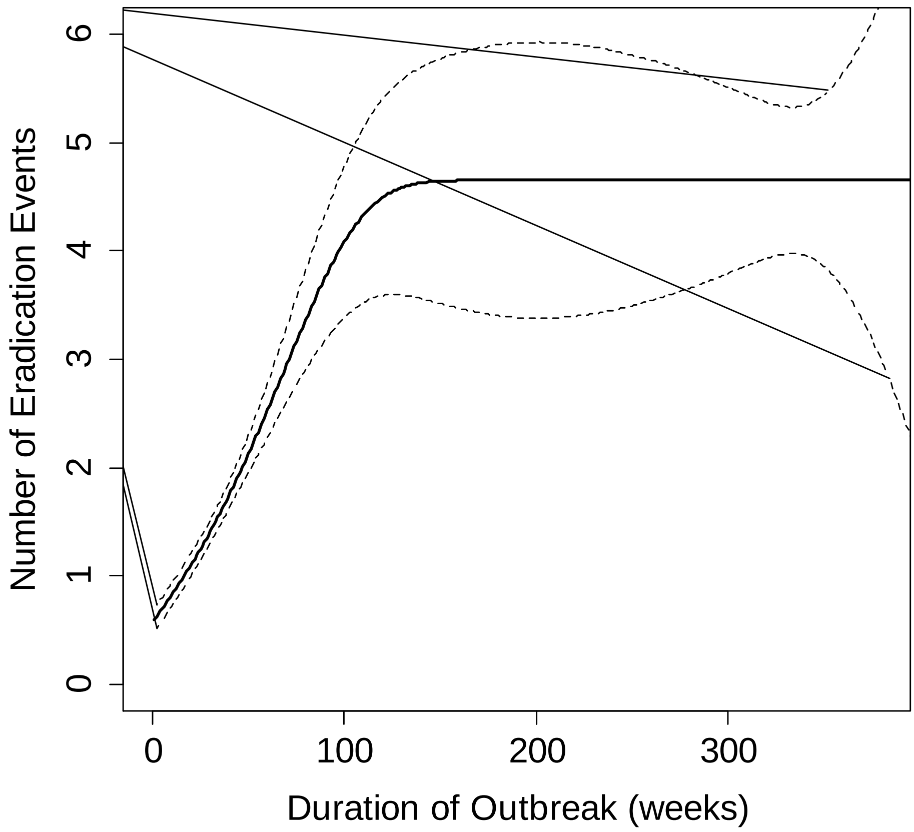

Figure 8. Predicting Number of Eradication Events from Outbreak Duration

Market Costs: Post-Harvest Treatment Costs

Market costs were defined as the post-harvest costs incurred from the time of declaring an outbreak to the declaration of pest free status following satisfaction of the one generation rule, and covering all production within a 15 km radius of the outbreak. A one generation rule was preferred in this instance to enable a greater number of defined outbreaks for ease of estimation of the probability of outbreak model. The market rule can be corrected for simply by defining its seasonal relative risk from the PestMon data (Figure 7). Post-harvest costs per tonne of table grapes, citrus and stone fruit were on average given as $127, $93.25 and $50, respectively, by major packing sheds in the region. These numbers differ from the $50 per tonne for each product included in the BCA of Ha *et al.* (2010). Post-harvest treatment costs were only valued within the Sunraysia PFA, with post-harvest treatment costs within the remainder of the FFEZ treated as fixed.

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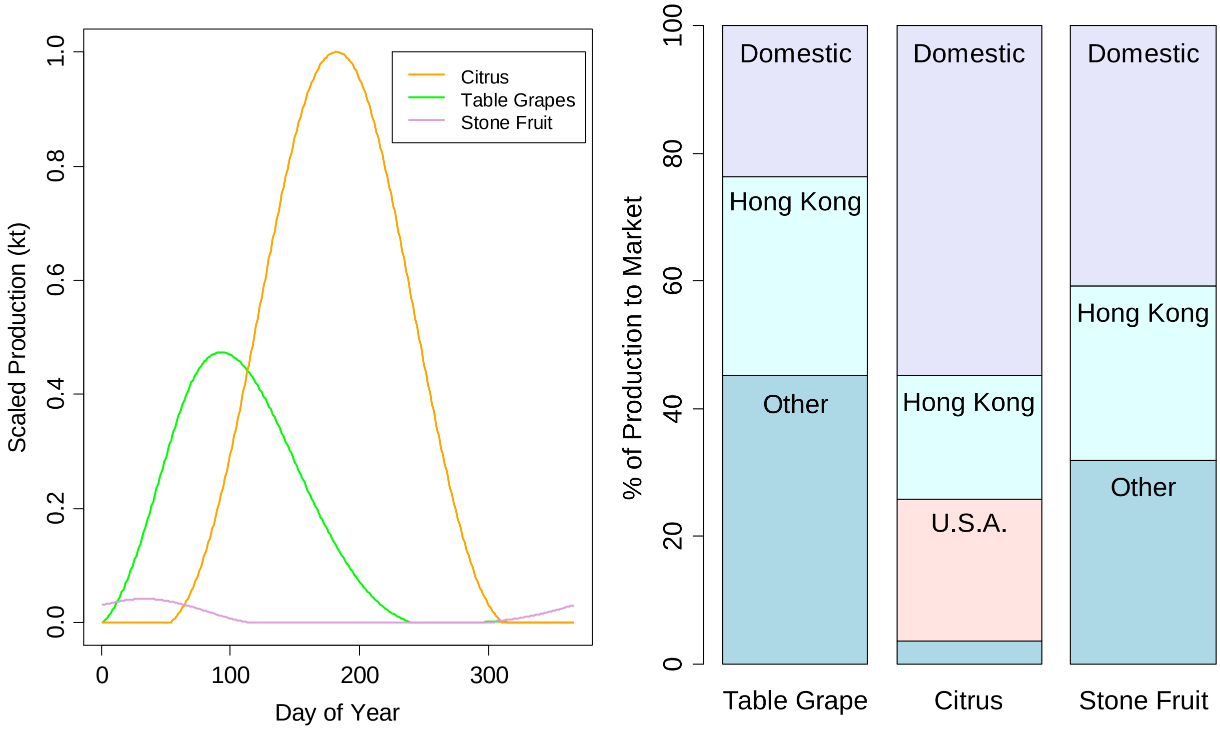

Figure 9. Time Varying Production and Market Share [Source: ABS, 2006]

The per week production for each crop for each map pixel was computed from land use data, provided by the Bureau of Rural Services (2010) as a 1:50,000 vector map, with 20 tonne/ha/yr defined for grape and stone fruit production, and 50 tonne/ha/yr for citrus production. Of the grape production 21.8% was destined for the dried grape market, and 62.6% for wine making, leaving 15.6% of production as table grapes (SunRISE 21 Incorporated, 2006). The value of post-harvest treatments was calculated only on table grape production, and similarly post-harvest treatments for citrus was considered only for 50% of total production, with the remainder of production destined for juicing. The temporal pattern of production for each crop type is known for the region from monthly market volumes, both domestic and export (ABS, 2006; Figure 9). While the land use map differentiated between vine and fruit tree production, fruit tree production was further split into 82.9% citrus and 17.2% stone fruit by hectare (ABS, 2006; this is similar to the 84.5% citrus and 15.5% stone fruit calculated from SunRISE 21 Incorporated, 2006). The proportion of each landscape pixel covered by vine crops and fruit trees (both irrigated and rain-fed for each crop type) was calculated. Knowing the area of production for each pixel and each crop type permitted a production curve to be assigned to each pixel, with weekly post-harvest costs computed accordingly. **The total yearly post-harvest treatment costs to be potentially avoided through implementation of the Sunraysia PFA was thus valued at $39.3 million per annum, with 71.0% or $27.9 million of this benefit accrued in Victoria.** Valuation of these benefits using the post-harvest costs of Ha *et al.* (2010) returns a benefit of $19.8 million for the whole PFA, or 50.4% of our valuation. Interestingly, the Ha *et al.* (2010) benefit within the Victorian part of the PFA is 70.0% of ours at $13.8 million (or 49.9%).

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Simulation of Post-Harvest and Eradication Costs

Monitoring was restricted to those grid cells across the FFEZ with a proportion of residential and horticultural areas, together, greater than 0.28. This proportion equated to the rate of landscape grid cells currently monitored under the PestMon database within NSW. The procedure for simulating outbreaks and their post-harvest costs is as follows:

1. Generate an expected probability of outbreak for each landscape grid cell and each week, given weekly varying climate at each level of surveillance effort (measured as the spacing between individual traps in a surveillance grid, or equivalently trap density).
2. Simulate as binomial trials the locations and timing of potential outbreaks, given the spatially and time-varying probability of outbreak.
3. Generate an outbreak duration for each potential outbreak. This uses a multinomial logit model to assign outbreaks to a given duration 'class', given a distribution of initial captures, and estimated from the available PestMon data (Figure 11). The annual pattern of time to market recertification is one of rapid increase in late summer followed by a slow decrease to start of summer values. This pattern was repeated for the three classes, with key correlates predicting class membership including trap density and the local proportion of residential and horticultural areas. The distribution of initial captures was inferred in a two stage process: (i) the distribution of time varying and unobserved initial population numbers at the time of population arrival was inferred through simulated maximum likelihood (Diggle and Gratton, 1984), with this framework borrowing much from empirical likelihood methods (Owens, 2001); and, (ii) for each level of surveillance effort the model of local population growth and dispersal was forward simulated to generate a distribution of initial captures (Figure 10). These procedures are specified in greater detail in Sadler *et al.* (2011), and Sadler *et al.* (2012a), being dependent on: the probability of individual trap capture rates; the rate of dispersal; the rate of population growth (inferred from Yonow *et al*. 2003 as a metamodel); and the regime of trap inspections and locations.
4. Clean the outbreaks of any that fall within the 15 km suspension zone of a previous but active outbreak, giving the simulated outbreaks. Generate the number of eradication events from the duration of outbreaks (Figure 8), and compute eradication costs. Eradication costs are tied to the origin of the outbreak, and hence to a landscape grid cell.

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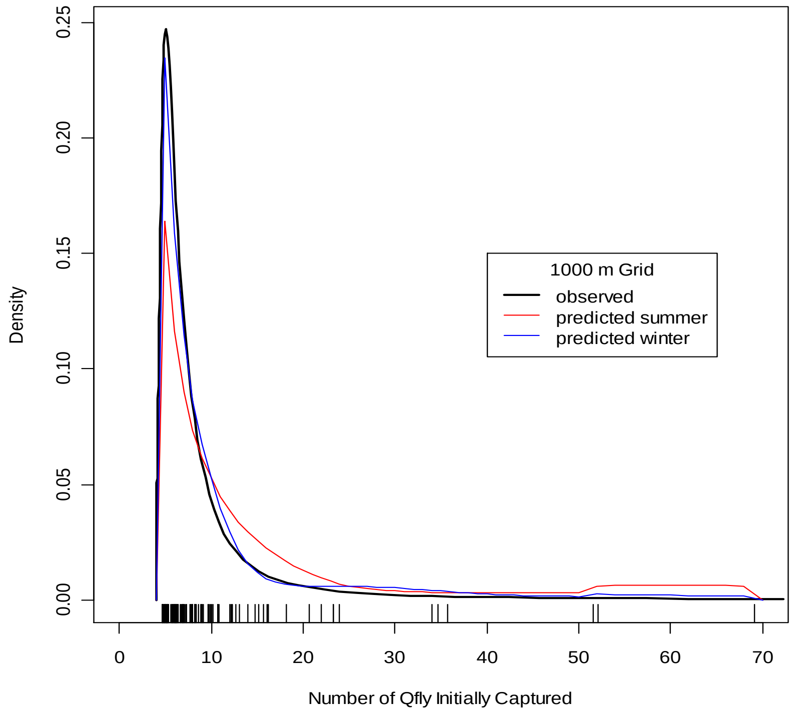

Figure 10. Modelled Distribution of Captures

5. When computing the actual post-harvest costs incurred the 15 km suspension zones assigned to each outbreak overlap both in time and space. The average proportion of each pixel's production and post-harvest costs already counted or incurred by one or more outbreaks in neighbouring pixels may be rapidly computed by assuming a simple geometry of independent intersections (i.e., the inclusion-exclusion principle). Consequently, outbreaks declared external to the PFA, but within 15 km of the PFA border, were also tracked for post-harvest costs incurred within the PFA. Market costs were incurred for as long as an outbreak endured, and were therefore dependent on the time to detection and surveillance effort (Figure 2).

This procedure underestimates the eradication costs insofar as an initial outbreak's suspension zone is not extended to 30 km once second and further outbreak declarations are triggered within the initial 15 km zone. This market rule can be incorporated into the current model with further work. However, our probability model excludes an explicit spatio-temporal autocorrelation structure among outbreaks. **We recommend that the incidence of further outbreak triggers within an initial suspension zone should be examined probabilistically using the available PestMon database.** This will also help quantify the frequency by which control measures do not succeed to contain a dispersing Qfly population within a 15 km suspension zone. **An analysis of this type will assist in identifying which size of suspension zones are biosecure for current and future markets, in support of evidenced based policy and market regulation.**

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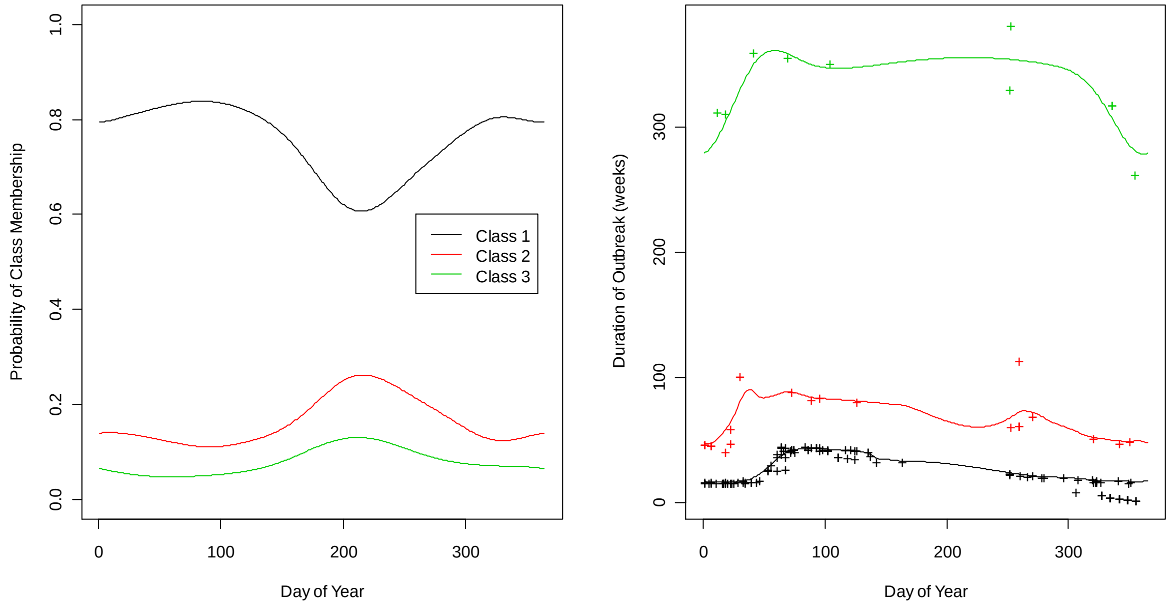

Figure 11. Outbreak Duration Model

Three distinct trends predicting the duration of outbreaks from the time of year were clear in the data (crosses in right figure, with fitted trend lines). The three trends, or classes, are: (1) short duration; (2) medium duration; and, (3) long duration (left figure). The probability of a declared outbreak's having membership to each trend (i.e., class) was observed to vary with time of year, as with initial population captured and trap density, with class membership predicted by a multinomial logit model. An outbreak duration is then calculated deterministically from the fitted trend line associated with each class, once a class is assigned through random simulation over the predicted class membership probabilities.

Cost of Surveillance

The cost of surveillance was taken to be a function of both trapping grid density and frequency of trap inspection (Figure 12), though for simplicity only the trapping grid density for weekly inspections was studied in terms of post-harvest and eradication costs. The cost surface was derived from costs for labour, trap maintenance and travel time, and is multiplied by the number of traps in the landscape (Florec et al. 2010a). A grid cell was assigned a trap if the sum total of vine, fruit tree, other horticultural and residential land uses exceeded 0.28 of total pixel area, a threshold derived from the PestMon trap data.

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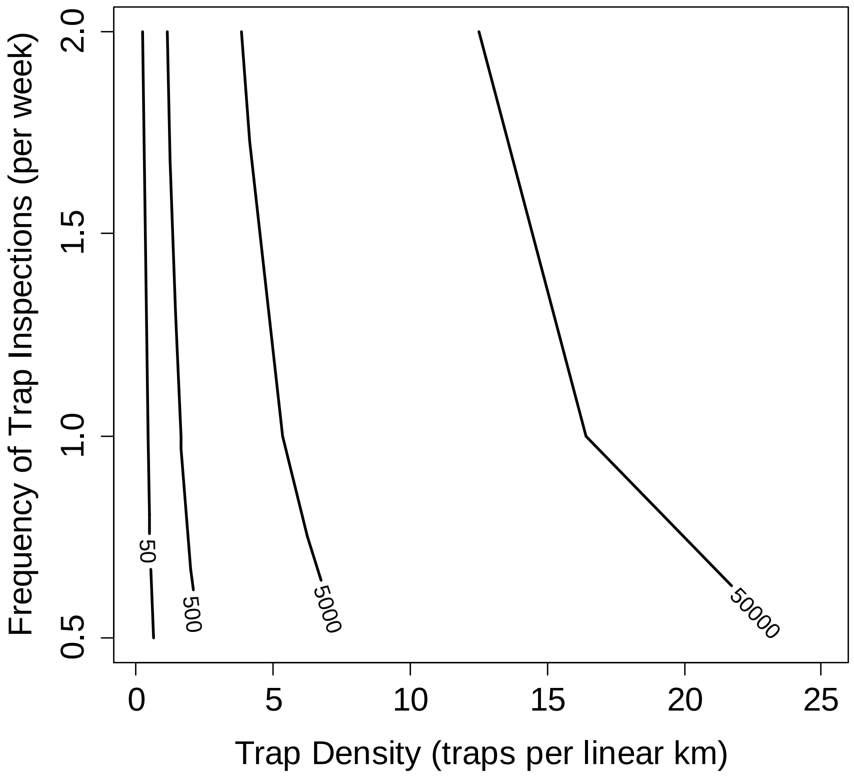

Figure 12. Surveillance Cost Surface: Grid Density and Frequency of Trapping ($/km^2).

Benefit-Cost Results

"When in doubt, smooth."

Sir Harold Jeffreys, quoted by Moritz, 1980, Advanced Physical Geodesy

Time to Detection of Unobserved Arrivals by the Surveillance Grid

An important output of our bioeconomic approach was that some measure of the effectiveness of a surveillance regime in detecting an unobserved and randomly arriving Qfly population could be provided, not only in economic but also in physical terms. Furthermore, an understanding of the physical process, i.e., the population ecology of Qfly, gives a better understanding of the economic value of surveillance. Note that in the results there is substantial 'simulation-induced' variability due to the probabilistic approach taken, which means that despite smoothing occasional spurious features are observed in the simulated data. Our method of measuring time to detection throughout is as the conditional probability of the time to an outbreak being declared from arrival, given that a population arrival will lead to a declaration of outbreak. This is in contrast with a strict definition of a waiting time to the first detection of any individual, and differs only in it being a waiting time until a minimum threshold number of captures.

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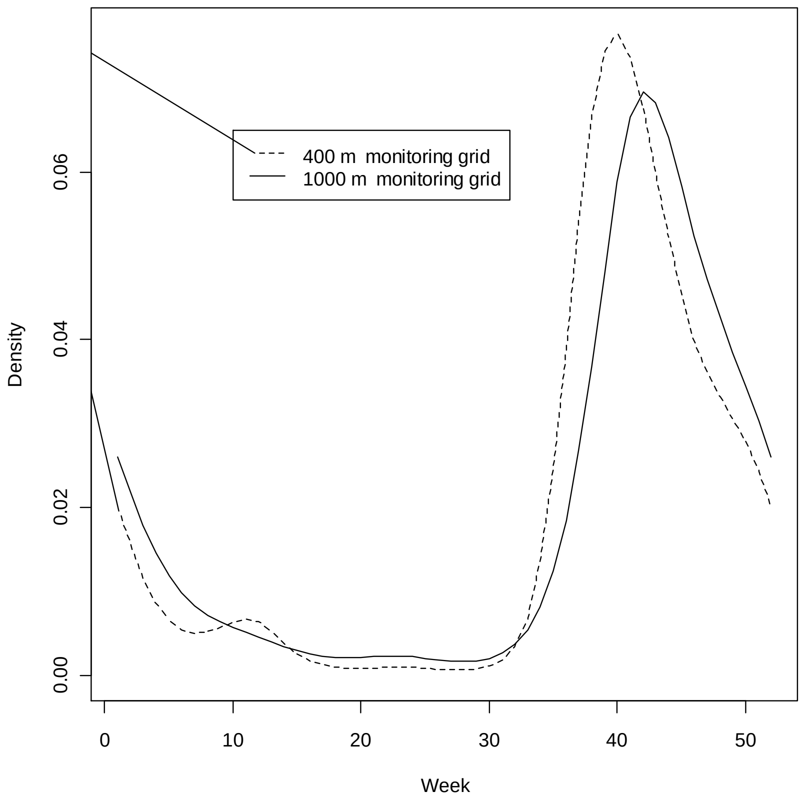

Figure 13. Timing of Declarations of Outbreaks (Week of Year)

The time to detection varies with time of year and, in addition to the surveillance effort invested, is dependent on: (i) when a population arrives; (ii) the specific local history of climatic events following arrival that determines how fast a population grows and disperses; (iii) the size of the initially arriving population (assuming it survives population allee effects); and, (iv) the probability of individual Qfly being captured by a trap. Hence there is a differential lag between the time of population arrival and the time to declaration of an outbreak, which is seasonally varying (illustrated in part by Figure 6 for the current surveillance regime within the NSW FFEZ, which indicates the lag between when flies are first captured and when an outbreak is declared). For instance, a 400 m surveillance grid will declare a greater proportion of its outbreaks than a 1000 m grid at the start of the Qfly season (spring or week 32 of the calendar year; Figure 13).

Time to detection can vary significantly with time, with mean time to detections varying by 6-8 weeks over the year (Figure 14). A bimodal character is evidenced, typical of Qfly, with greater waiting times in mid-summer and mid-winter, with population growth rates diminished in those periods by drought stress and cold stress respectively. In essence, a population that grows slower will take longer to detect as it will take a longer time before the population crosses a detectable size threshold. Similarly, **the benefit in terms of earlier detection of a greater investment in surveillance varies over the year** (Figure 14). The 600 m and 1000 m surveillance grids are comparable in that they share the same number of traps within a 1 km radius of one trap, as defined by the current market rule for a declaration of outbreak. The benefit of the 600 m over the 1000 m grid is that any one trap in the 600 m grid will be closer on average to the

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location of the Qfly population arrival, thus on average the growing population will reach the threshold required for the declaration of the outbreak sooner, leading to an earlier time to detection. However, this benefit is not realised in the summer months, because the period of diminished net growth rates is smaller, and growth rates on average are greater. The number of Qfly local to a trap in the 1000 m surveillance grid can as rapidly increase past the detectable threshold as for a 600 m grid, when population growth rates are significantly higher. As a weak condition, all that is required is for the net growth rate to be greater over the summer months than the winter months, proportionately more so than the ability of a 600 m grid to detect a new population over the 1000 m grid (Sadler et al., 2012a). This result is accentuated by the estimated dispersal kernel, defining the probability of a Qfly population dispersing at different distances, as being leptokurtic (or ‘fat-tailed’; Sadler et al., 2011).

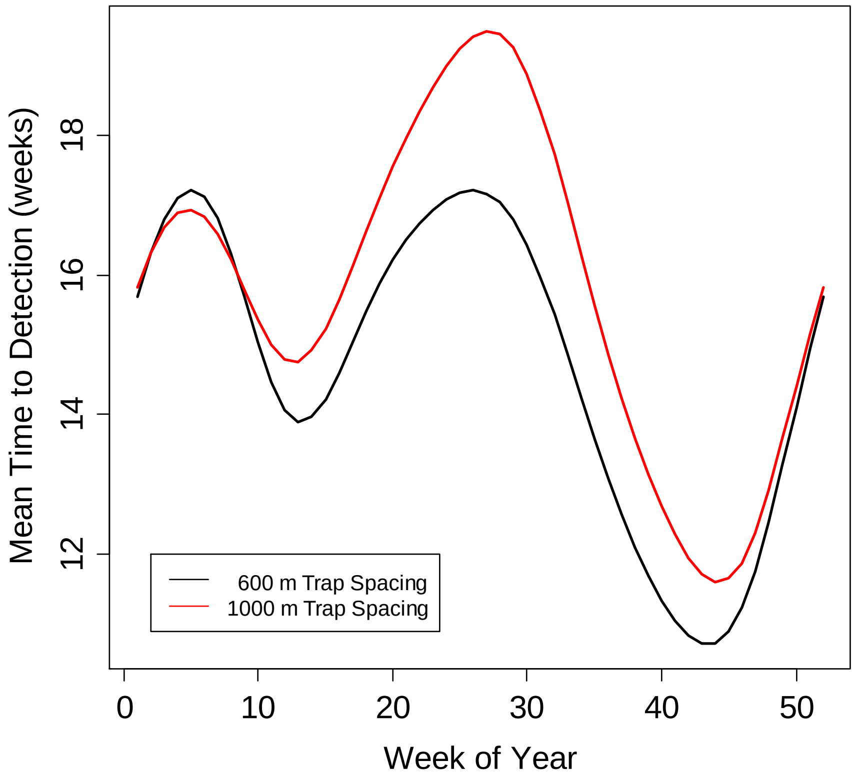

Figure 14. Time-Varying Mean Time to Detection

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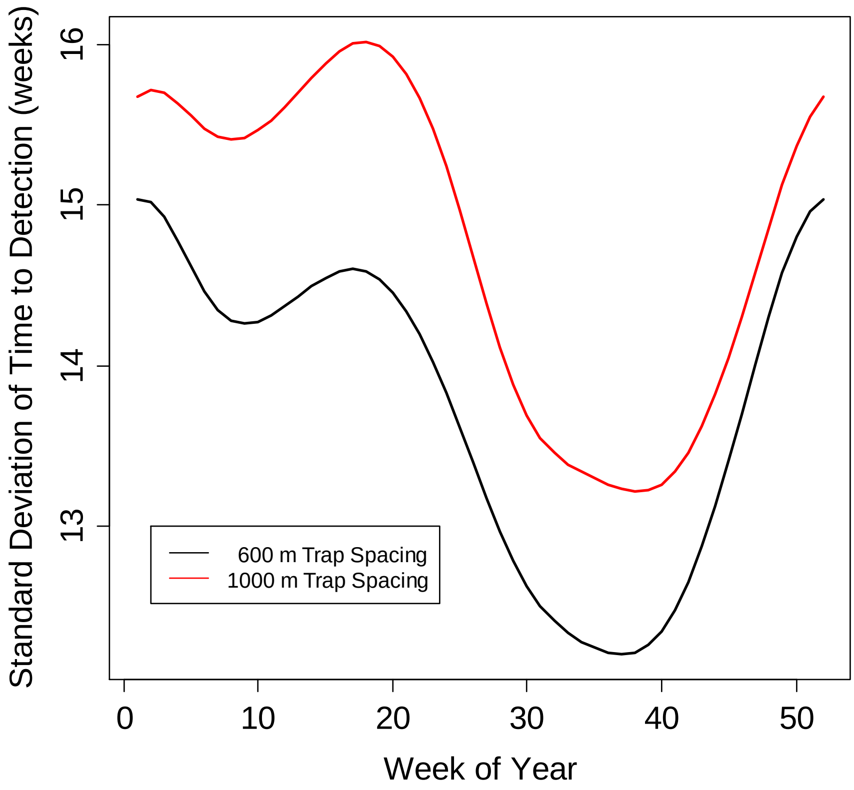

Figure 15. Time-Varying Standard Deviation of Time to Detection

Leptokurtic dispersal kernels result in populations being more evenly 'smeared' over a landscape, with relatively little difference between the number of Qfly captured in a trap further away from point of arrival, and one located nearby. Only when there is a significant increase in the number of traps in a landscape may the likelihood of earlier detection increase, especially in the presence of a market rule for the declaration of outbreaks that counts the number of captured Qfly within a fixed 1 km radius. This can lead to a 'flat' response of time to detection to an increase in surveillance intensity (Figure 16). However, while the benefits of increased surveillance in terms of decreasing mean time to detection may be small, increased surveillance does lead to a reduction in the range of variability in time to detection (Figure 15). Again, the maximum distance between the nearest trap in more dense surveillance grid an outbreak is less than that for a coarser grid, thus reducing time to detection variability. The benefits of increased surveillance may then be more about reducing the probability of large, spatially extensive Qfly populations at the time of an outbreak declaration.

Net Benefit of the Current AWM Strategy

As discussed previously, we value the total potential benefit of the FFEZ scheme at $39.3 million with 100% avoidance of post-harvest treatment costs in the scenario where no outbreaks occur ($19.8 million if using the post-harvest costs of Ha *et al.*, 2010). The costs of the scheme then needs to be deducted from this total potential saving, i.e., the expected annual post-harvest treatment and eradication costs incurred as the result of outbreaks, as well as the cost of maintaining the current regime of surveillance (400 m spacing in residential areas and 1000 m in horticultural production areas). Here, we estimate as a 17 year average the eradication costs at $0.79 million per year (standard error 0.08 million per year), and post-harvest costs at $5.4 million per year ($4.6 million

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per year standard error). This can be compared with post-harvest costs given by Ha et al (2010), with post-harvest costs of $2.3 million per year (standard error $1.0 million). This means that the ratio of realised post-harvest costs to total potential benefit is 13.7% in our model when production and outbreaks are spatially and temporally disaggregated (11.6% for Ha *et al.*, 2010 post- harvest costs). Monitoring costs for the scheme were estimated at $0.79 million per year. This results in **total net benefits of $23.6 million per year**, less any administrative costs[5].

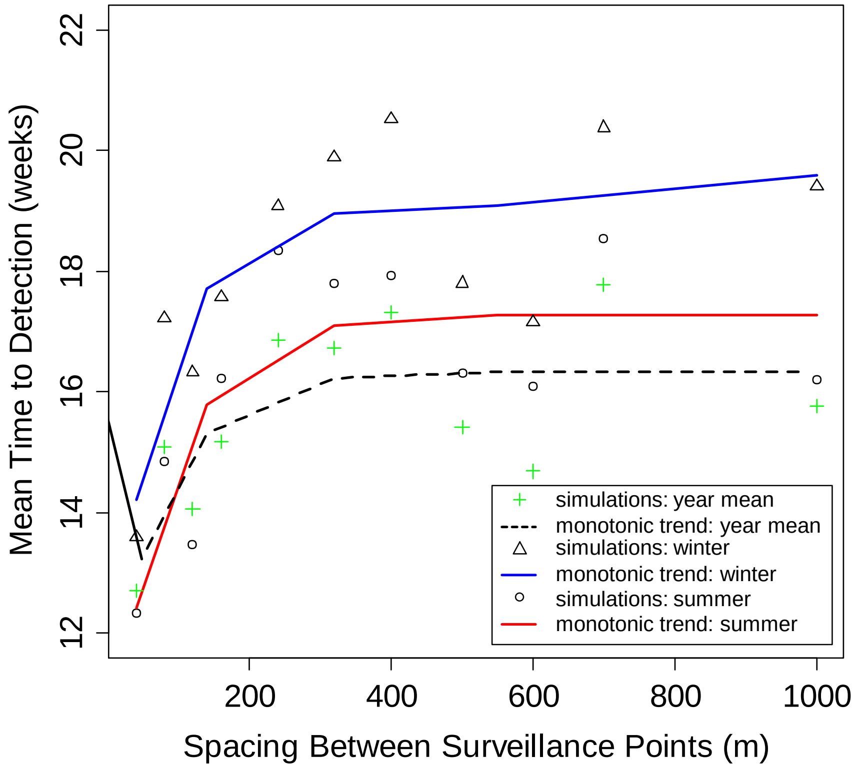

Figure 16. Surveillance Effort and Mean Time to Detection

[5] The benefit-cost ratio would be 21.2 if post-harvest costs are included on the benefit side (i.e., expected benefit = total potential benefit – expected post-harvest costs). If not, then the benefit-cost ratio would be 5.6. In comparison, the post-harvest costs of Ha et al. (2010) results in net benefits of $15.9 million, and equivalent benefit-cost ratios of 10.9 and 5.1.

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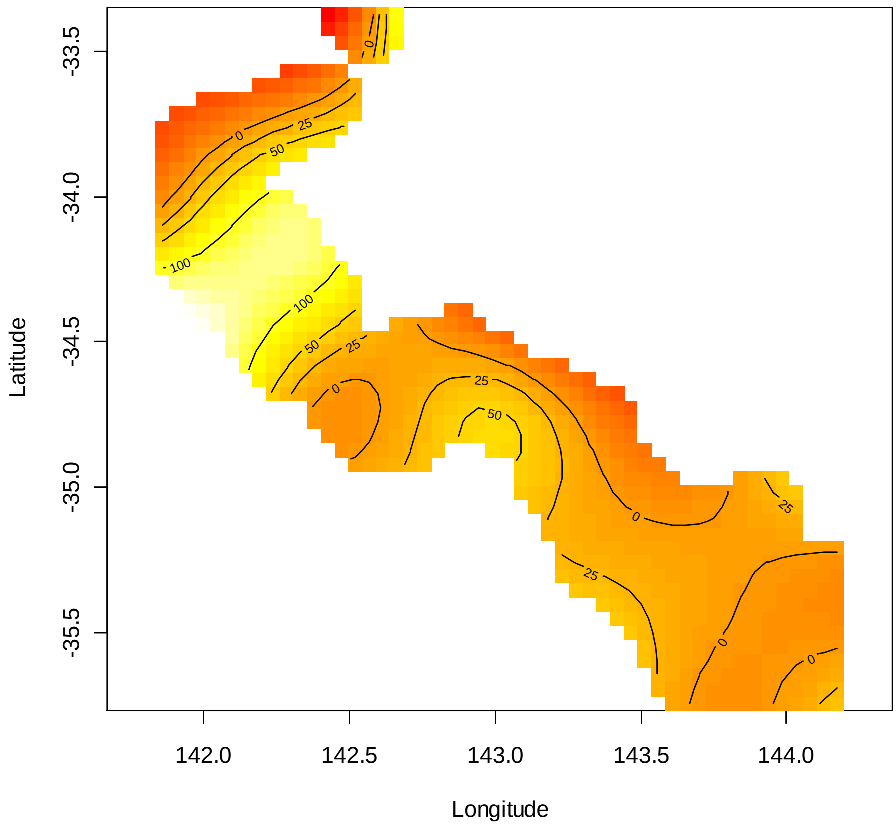

Figure 17. PFA Postharvest Treatment Costs with Current Monitoring (smoothed $/ha/yr)

A break-down of the benefits by region (PFA or non-FFEZ, NSW or Victoria) is given in Table 4. As post-harvest treatment costs resulting from outbreaks are incurred at each point within the Sunraysia PFA then the smoothed distribution of post-harvest treatment costs may be plotted. The 'hotspot' in costs is around the Mildura production region, corresponding to the region of greatest production value within the PFA (Figure 17).

A key limitation of the results presented here is that surveillance was generalised only to those areas with greater than 28% of local land use assigned to either horticultural production or residential areas. The generalisation was necessary, though *ad hoc*, so as to extrapolate the benefit-cost analysis to the Sunraysia PFA from the NSW non-PFA areas reported in the PestMon database. This generalisation has naturally biased the selection of surveillance sites towards horticultural areas, however it is these areas that tend to have a lower reported rate of outbreaks within the model. For instance, the model surveillance sites had on average a mean 40% of local area as horticultural production, whereas the FFEZ average for all sites with at least some horticultural production or residential areas was closer to 10% of local area. The consequence is a significant under prediction of the total number of outbreak events, and hence reduced eradication and post-harvest costs. This issue can be rectified through access to Victorian trap data (as well as South Australia) under the aegis of BioSirt (http://www.daff.gov.au/animal-plant-health/emergency/biosirt). A 'guesstimate' of the magnitude of this effect is of a potential doubling of the eradication costs and an increase in yearly post-harvest costs by 50%, potentially reducing net benefits to

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approximately $28 million[6]. In contrast, the probability of outbreak model accurately reproduces the distribution of outbreaks for the PestMon database when predicted at the current PestMon surveillance sites within NSW.

Economic Evaluation of R & D and AWM Strategy Options

The behaviour of Qfly populations interacting with a surveillance grid may be characterised from a biosecurity perspective as a waiting time distribution, or time to detection. Our working assumption is that a delay in detection will have significant economic consequences, as it allows populations to build up to the extent that they are: (i) difficult and costly to eradicate; and, (ii) result in longer periods of market access loss, and consequent increased expenditure on post-harvest costs within the PFA. We term this assumption the Kompas-Che biosecurity hypothesis (Figure 2; Kompas and Che 2009). Our mechanism for computing the costs in practice considers the dual of the time to detection distribution, namely the distribution of captures at the first point in time when these captures exceed the declarable threshold that defines an outbreak (Figure 10). However, the link between initial captures and the level of surveillance effort is not one-to-one: while a coarser surveillance grid will lead to greater initial captures at individual traps, a finer resolution grid may well have a greater total number of captures due to the larger number of traps. We avoid this issue by modelling the time-varying duration of an outbreak (from declaration to market recertification under a 'one generation' rule) directly from trap density and initial captures using the PestMon database (Figure 11). This duration of an outbreak 'overlays' production seasons of different horticultural crops, from which post-harvest treatments are calculated (Figure 9). Similarly the suspension zone overlays a spatially heterogeneous area of production buffering the point of an outbreak declaration. While eradication costs are simply calculated from the number of outbreaks, with the duration of the outbreak factored in, the post-harvest costs are integrated over space and time and, importantly, weighted by the time-varying probability of outbreak that accounts for spatial and climatic factors.

Investment in each of the AWM strategy options can influence one or more of these component costs. For instance, the strategic investment 'bucket' of surveillance effort determines the time to detection, given the seasonal population ecology of Qfly. Furthermore, high density surveillance grids reporting more outbreaks on average as they can detect 'spurious' populations that would otherwise self-extinguish unobserved on low density surveillance grids through an allee process. This effect is suggested by the PestMon data, and included in the probability of outbreak model (Figure 7). This chain of reasoning can be applied to the other AWM strategy options and summarised in Table 1. A simple means of evaluating the value of investment in research and development options (R & D) to the FFEZ AWM scheme is a sensitivity analysis: calculate the net benefits by increasing the value of a parameter within the bioeconomic model by, say, 10%. This values R & D as the potential cost saving, or net benefit, resulting from

[6] By nature of its design Q-FLAWM will provide lower estimates of post-harvest treatment costs. Production occurs over a limited window, both in space and time, and has to coincide with the timing and location of outbreaks. Hence, post-harvest treatment costs will be lower than in aggregated BCA models that pool both costs and the number of outbreaks over regions larger than individual suspension zones.

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an R & D option achieving that level of operational benefit. It would then be left to the R & D investor to determine the ease with which an operational benefit can be realised and its investment cost. A more comprehensive framework for R & D prioritisation is sketched at the conclusion of this report.

Even with a comprehensive bioeconomic model in place, some of the R & D and strategy options are difficult to evaluate. The Q-FAWM model, by disaggregating cost and benefits, places an upper bound on the returns to R & D. For instance, the highest return from remote controlled traps is approximately the reduction in labour required to monitor those traps. Here, we will consider only a few of these options:

1. Investment in border control to reduce the overall probability of outbreak by 10%, with a consideration of seasonal benefits.
2. Investment in eradication such that the duration of an outbreak is reduced by 10%.
3. A spatially heterogeneous and optimal investment in surveillance effort (i.e., trap density of the surveillance grid).
4. A 10% reduction in each of eradication, surveillance and post-harvest costs, and its influence on the optimal surveillance strategy.

Border Control: Reducing the Probability of Outbreak

Effective border control resulting in a 10% reduction in the overall probability of outbreak will directly reduce eradication costs and post-harvest costs (fewer outbreaks). The value of this improved border control was estimated as $0.5 million per annum in total (Table 2). One consideration of border control is that its benefit may differ between seasons, given the probability of outbreak differs between seasons, as does the timing of when post-harvest costs are incurred and their subsequent durations (Figure 11). The benefit of border control is greater during the winter season, and when normalised to yearly returns, is valued at $0.62 million per year, as opposed to a $0.42 million per year benefit of increased border control in summer months (Table 3). This is a counterintuitive result in that the probability of an outbreak is greater during the summer months. However, outbreak durations are much shorter, contributing to lower post-harvest costs overall. **Benefits of effective border are higher during winter months than the summer months.** The benefits of border control are also greater at increased levels of surveillance (Figure 18 – black line).

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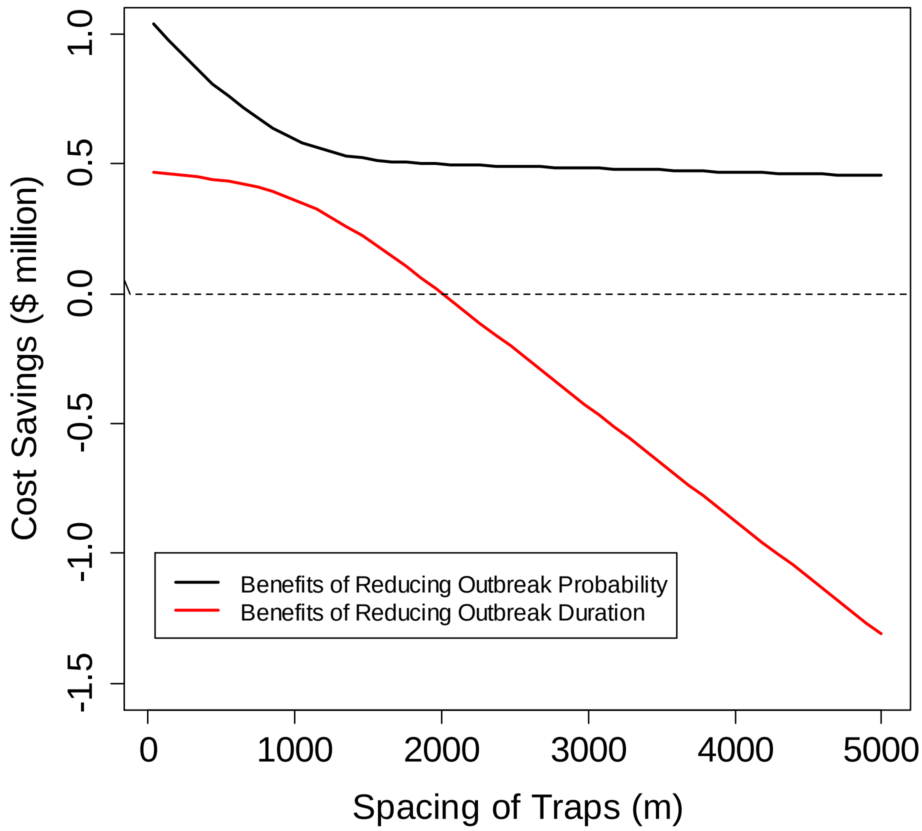

Figure 18. Cost Savings from Two Technologies for Different Surveillance Grids

Eradication: Reducing the Time to Eradication

There are a number of ways to define the possible benefits of improved benefits, however, we consider eradication benefit as a 10% reduction in the duration of each simulated outbreak. The benefits of eradication are then in terms of reduced post-harvest costs. Under the current surveillance regime the net benefit of a 10% reduction in outbreak duration was estimated at $0.43 million per year. As outbreak duration is also a function of trap density, the relationship between surveillance effort and improved eradication outcomes can be examined. Significantly, **savings due to a 10% reduction in the duration of outbreaks is less than savings on a 10% reduction in the probability of outbreak** (Figure 18). Moreover, at trap spacings greater than 2000 m benefits calculated by the model are negative. A rationale for this result is that lower levels of surveillance are associated with longer outbreaks in the model, and so a long duration outbreak may mask a significant number of other population arrivals, and hence potential outbreaks. Thus while duration is reduced, a consequence is that the number of outbreaks increases, resulting in diminished benefits.

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Table 1. Investment in Strategy and R & D: Options and Strategic Buckets

AWM Stategy ('strategic bucket')	Likely Economic/ Social Benefits	Possible Economic/ Social Negatives	R & D and Strategy Options	Likely Investment Outcome	Possible Detractions
Sentinel Surveillance	Earlier detection; reduced outbreak duration and reduced post-harvest costs	Greater rate of declaration of outbreaks due to detection of spurious populations	Better local trap placement (De Lima; Clarke).	Decreased labour costs (fewer traps needed) and/or earlier detection	Higher labour costs with the need to move traps seasonally. May have implications for rules such as counting all captures within 1 km radius for a declaration of outbreak.
			Automatic/Remote traps	Decreased labour costs	Higher establishment costs of surveillance grid
			PDA recording of captures.	Flow on effects to other R & D given better information availability. Lower information error rates during information translation	Database establishment and integration costs
			Increased capture effectiveness	Earlier detection	May require alternative management - establishment and maintenance costs
			Variation of surveillance grid resolution	Greater economic optimality	May lack equity among producers, with unequal access to different markets.

Border Control / Education	Reduced probability of outbreak across region. Greater vigilance by population, and hence earlier detection, especially in non-monitored areas (i.e., passive surveillance).		Better community education programmes	Better passive surveillance and reduced probability of outbreak.	Higher costs Difficult to measure outcomes
			Increased vehicle inspection	Reduced probability of outbreak	Higher costs Individual rights Difficult to measure outcomes
			Increase extent of buffer areas such as the non-PFA region of the FFEZ		Higher costs Uncertain effectiveness, particularly in regions that are ecologically more hospitable to Qfly, and importance of local continuity of residential and horticultural areas for population diffusion.
Eradication	Reduced market loss and post-harvest costs.	Indirect effects of chemical based controls.	Improved SIT (Katrina; other)	Reduced market loss and reduced reliance on chemical controls.	Carry greater risks of ineffective control due to varying or extreme environmental conditions.
			Increased eradication effort (e.g., 16 weeks as opposed to 12 weeks duration; or increase eradication zone from 1.5km to 2.5 km)	Increases effectiveness of eradication in reducing market loss through repeat outbreaks at the one locality.	Higher costs
			Technology with decreased costs	Allows greater eradication effort, or reduced costs overall	

Pre-Harvest Control	Can provide a 'prophylactic' effect locally in production areas, reducing the probability of an outbreak, and eradication and market loss costs.	Indirect effects of chemical based controls.	Integrated Pest Management	Includes bait sprays, trapping and similar technology to reduce chemical reliance and improve prophylactic control (Clarke; more).	Higher costs. Decreased biosecurity.
Post-Harvest Control	Provides greater product biosecurity, enabling market access to otherwise at risk product.	Indirect effects of chemical based controls.	Better 'non-chemical' control (John Gold; De Lima)	Satisfies health and environmental concerns	Higher costs.
			Technology with reduced cost of post-harvest treatments.	Improves profitability of AWM scheme.	
Market Regulation	Trade certainty Better mirrors the population ecology of Qfly and associated risks	May not be optimal for local region/time.	Change in size of suspension zone to ecological optimum	Provides more accurate reflection of economic costs and benefits of achieving a desired level of biosecurity	Possible loss of markets, unless evidence-based.
			Change in declaration of outbreak rule (e.g., from 5 flies to 2 flies, or one km to 2 km in two weeks).	Provides more accurate reflection of economic costs and benefits of achieving a desired level of biosecurity	Altered costs. Possible loss of markets, unless evidence-based.
			Change in market recertification rule (e.g., from 1 generation and 28 days to 3 generations).	Provides more accurate reflection of economic costs and benefits of achieving a desired level of biosecurity	Altered costs. Possible loss of markets, unless evidence-based.

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			Areas of low pest-prevalence	Reduces cost associated with including endemically higher risk locations such as residential areas within a PFA.	Possible loss of markets, unless evidence-based.
			More PFA defined areas	More net benefits realised for community.	Greater public administration burden. PFAs may be extended into higher risk areas and be less effective.
Administration	Longevity of AWM	Self-interested jurisdictions	Long term administration and cost-sharing agreements between states and between public and private industry	Greater trade certainty, facilitating longer term investments in horticultural production and infrastructure	Difficulty of negotiation

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Table 2. Value of Improving Border Control: A 10% Reduction in the Probability of Outbreak ($ Millions)

Border control level	Probability of outbreaks (mean per week per grid cell over all FFEZ)	Average annual costs of incursions		Estimated expected Costs	Estimated benefits of a 10% improvement in border control
		Average annual eradication costs	Average annual post-harvest treatments		
Current	0.00028	1.31 (0.10)	5.24 (2.78)	6.55	0
10% improvement in border control	0.00025 (5.dp)	1.18 (0.09)	4.87 (2.72)	6.05	0.50

Table 3. Value of Improving Border Control: Seasonal Differences (evaluated as yearly cost; $ Millions)

Border control level	Probability of outbreaks (mean per week per grid cell over all FFEZ)	Average annual costs of incursions			Estimated expected Costs	Estimated benefits of a 10% improvement in border control
		Time to area-freedom reinstatement*	Average eradication costs per season	Average post-harvest treatments costs per season		
Current	0.00039	summer (short)	1.79	3.71	5.5	0
	0.00012	winter (long)	0.59	7.39	7.98	0
10% improvement in border control	0.00035	summer	1.62	3.46	5.08	0.42
	0.00011	winter	0.53	6.84	7.37	0.61

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Surveillance: Spatially Heterogeneous Optimal Solutions

A critical question of any AWM design is where, when and how intensely to surveil a region. Surveillance costs can be significant, and increase quadratically with surveillance effort (i.e., spacing between surveillance points) when arrayed in a grid. The performance of a surveillance grid may be measured in a number of ways including: time-to-detection, the prophylactic effect of early detection and hence ready eradication; the extent to which a resident population filters through the other AWM controls such as post-harvest treatments (e.g., probit-9 requirements to ensure market access); and the economically optimal level of surveillance. Surveillance thus presents a multi-goal decision problem: to maximise biosecurity while minimising economic costs, recognising that optimal economic behaviour may not coincide with optimal biosecurity action. Here we examine the problem of choosing a level of surveillance effort that maximises economic benefits (i.e., minimises total costs). Post-harvest, eradication and monitoring costs have been evaluated for each pixel in the landscape and compared with the optimum for a homogeneous surveillance strategy over the landscape.

The first result is that **in the absence of market regulation it is economically optimal to surveil at the lowest possible level**, if undertaking surveillance over the landscape at a single rate (Figure 19, left). In the Q-FAWM model higher rates of surveillance are penalised by a higher rate of outbreaks that would otherwise self-extinguish through allee effects, or coalesce into single outbreaks, under lower rates of surveillance. This higher rate of outbreak probability outweighs the potential benefits of reducing the duration of outbreaks through earlier detections. Note that the benefit of earlier detection is realised in terms of a local minimum for the post-harvest costs at a trap spacing of 550 m (Figure 9, right), at a point when the response of the outbreak probability plateaus (Figure 6), and reductions in outbreak duration can dominate the balance of costs. However, this local optimum is not observed in terms of total costs due to the dominating trend in monitoring costs with trap spacing (Figure 19). Eradication costs monotonically decrease after a trap spacing of 240 m, after an initial peak, reflected also in the post-harvest costs[7].

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[7] Again, an artefact of the model is reflected in the 'bump' in eradication costs for trap spacings below 240 m, for the same reasons as explained for the post-harvest treatment costs above. The conclusion to be drawn from this model artefact is that estimation of these costs from the available PestMon database is not reliable for surveillance investments of below 240m spacing. However, the artefact is irrelevant in the current case due to the dominating monitoring costs over this lower range of trap spacings.

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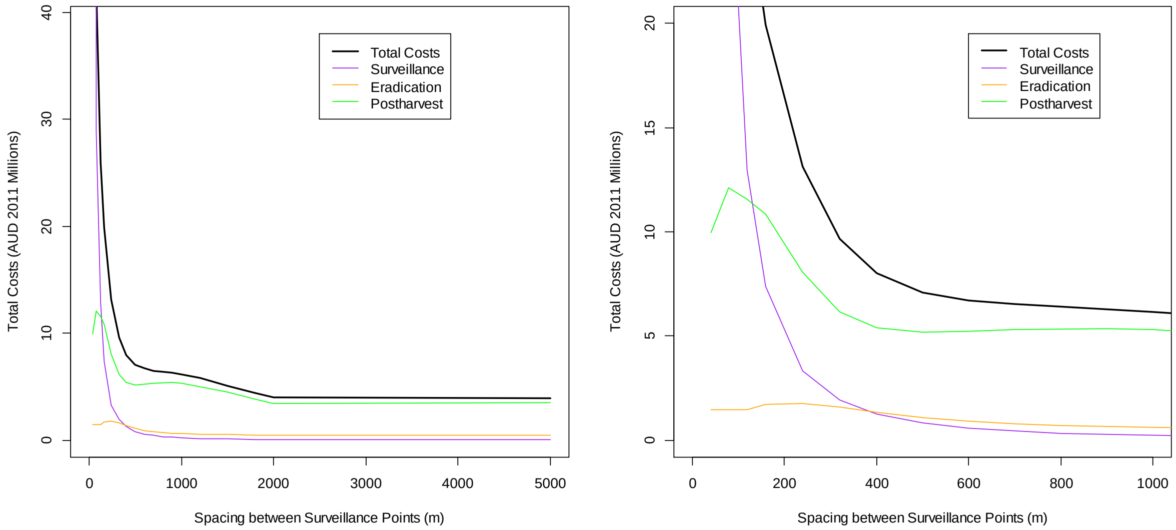

Figure 19. Costs of Area Wide Management with Surveillance Effort

Figure on right is a segment of left figure over the range of trap spacings from 0 to 1000 m.

While it may be economically optimal to undertake as little surveillance as possible, if pest-free status can be assured between outbreak events, it will not be optimal to undertake minimal surveillance if significant markets risk being lost altogether as a result of that lower level of surveillance. This reflects the current trade agreements where surveillance at every 400 m in residential areas and 1000 min production areas is required for pest-free trade to exist. This non-optimal rate of surveillance can be readily afforded, as the net benefits of engaging in AWM far outweigh the costs. The decision problem of determining an optimal rate of surveillance then becomes maximising net benefit, subject to a 'biosecurity constraint'. Without satisfaction of this constraint then there is no pest-free trade and hence no regional benefit of engaging in AWM. It is therefore economically rational to satisfy this biosecurity constraint, and engage in the required surveillance, given the trade agreements currently in place. The question regarding surveillance then becomes: **is it optimal to increase surveillance effort from the minimum specified by market regulation?**

Examination of whether the optimal investment in surveillance over the Sunraysia PFA may be different in different areas returns an intermediate result: **the optimal trap spacing varies between 700 and 1000 m** (Figure 20). The key reason for this result, and why optimal surveillance does not increase further in some areas, is again the dominance of monitoring costs in determining total costs as surveillance effort increases. When post-harvest costs are increased in a sensitivity analysis, or monitoring costs per trap greatly reduced, then the optimal surveillance strategy becomes increasingly spatially heterogeneous. The consequence is that with post-harvest costs doubled, optimal spacing of surveillance sentinels can decrease to 320 m in regions of high production value (i.e., high post-harvest cost regions in Figure 17). In these cases, post-harvest costs dominate when the penalty cost associated with increased outbreak durations becomes comparatively significant. This would be the scenario under market rules requiring greater time periods to relax before permitting market recertification

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(e.g., the three generation rule for citrus exports to the USA), or under a scenario of when comparatively cheap post-harvest treatment options are lost (such as current chemical controls).

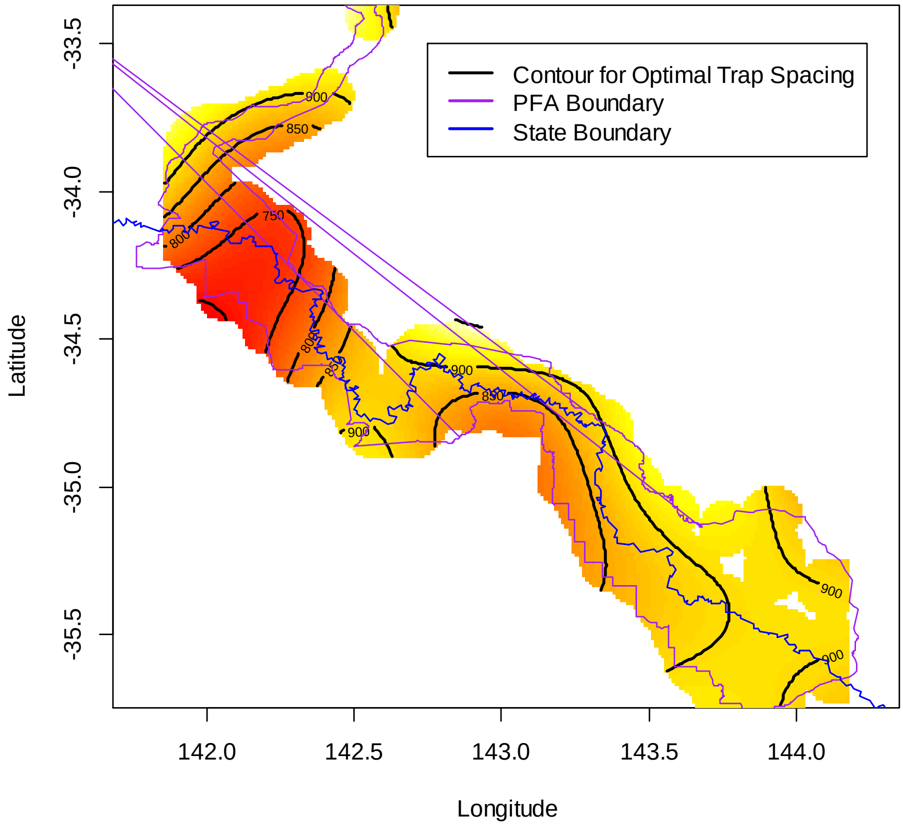

Figure 20. Spatially Optimal Surveillance Effort

Under the current set of technologies, where there is little benefit in spatially varying the level of surveillance effort, the optimal level of surveillance is predicted well by the local 'smoothed' value of yearly production (Figure 22; adj-$R^2 = 0.54$; p-value<0.0001). The main trend is clear: increase surveillance with increasing production value (even if marginally). However, two slightly different results are generated depending on how eradication costs are measured. In the first, eradication costs for the entire FFEZ are averaged on a per hectare basis for all parcels of land within in the PFA. This reflects the fact that while costs are incurred in the FFEZ the benefits are realised only within the PFA, and under a user-pays cost sharing model then all FFEZ costs should be assigned to the PFA. By including eradication costs in total costs then a 'threshold' effect is observed, in a (relatively) steeply decreasing response of optimal surveillance spacing to increasing production value, before a significant change in slope at $400/ha/yr. In contrast, when eradication costs are omitted, then the trend is to increase surveillance effort only slowly with increasing production value (Figure 22). Surveillance costs in this instance were not calculated, as it was assumed that under a biosecurity constraint then surveillance for the remainder of the FFEZ will be set the minimum required by market regulation. As no benefits are realised within the outer FFEZ region then there is no incentive to increase surveillance in that region. **The effect of a user-pays cost sharing arrangement is to increase surveillance when production value is high.**

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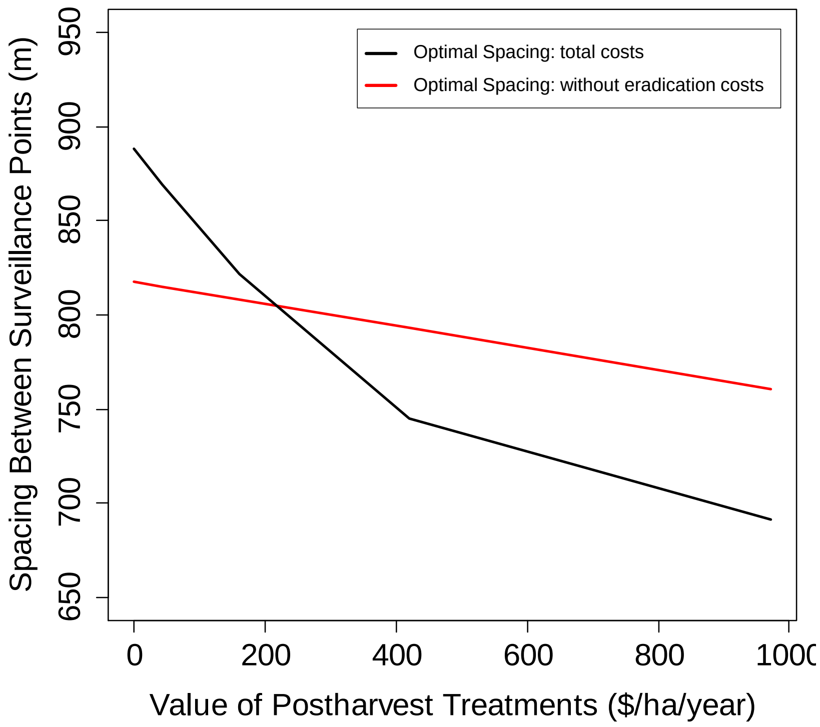

Figure 21. Predicting Optimal Sentinel Spacing from Value of Postharvest Treatments

Net Benefits: Current and Optimal Surveillance

We consider: (i) a regional break down of where the benefits and costs of the current AWM scheme are accrued; (ii) how these benefits and costs compare with a scenario with no AWM; and (iii) the possible value of applying the optimal and spatially heterogeneous rate of surveillance implied in the above section (Figures 20 and 21). In the absence of an AWM scheme post-harvest costs are incurred on all production across the region (Table 4: Scenario 1). These annual costs are significant and total $124 million, and do not include the value of either wine grapes, dried grapes or juicing citrus production. The majority of these costs are borne in the non-PFA regions of the FFEZ, predominately within NSW, and hence do not feature in the BCA. The benefits of AWM are in post-harvest treatment savings accrued solely within the PFA ($39.3 million, with the majority of the benefits accrued within Victoria). Further investments in maintaining surveillance and undertaking eradication are required to support the current AWM scheme, and are spread across the entire FFEZ, realising a net benefit of $32.4 million (Scenario 2). Significantly, if surveillance effort is permitted to vary in an optimal manner across the Sunraysia PFA, while kept to its current schedule across the remainder FFEZ, then surveillance costs vary little, but further benefits of $0.6 million may be achieved (Scenario 3).

Table 4. Benefit Cost Valuation of Different AWM Scenarios

			COSTS (AUD) / year[1]			
			Surveillance	Eradication	Post-harvest[2]	Total/Difference
Scenario 1: No AWM	NSW	PFA	0	0	11397098	11397098
		FFEZ	0	0	95765149	95765149
		Total	0	0	107162247	107162247
	VIC	PFA	0	0	27908456	27908456
		FFEZ	0	0	38957685	38957685
		Total	0	0	66866141	66866141
	Total	PFA	0	0	39305554	39305554
		FFEZ	0	0	106814378	106814378
		Total	0	0	146119932	146119932

1. Red: cost; Black: benefit
2. Post-harvest costs for regions outside of the PFA estimated using the mix of land uses within the PFA.

Scenario 2: Current AWM Extent Current Monitoring	NSW	PFA	38059	90651	9832335	9703625
		FFEZ	411122	180673	0	591795
		Total	449182	271324	9832335	9111830
	VIC	PFA	187665	15473	24104457	23901319
		FFEZ	157003	505596	0	662599
		Total	344669	521069	24104457	23238720
	Total	PFA	225725	106124	33936793	33604944
		FFEZ	568126	686269	0	1254394
		Total	793852	792393	33936793	32350550

3. Red: cost; Black: benefit; calculated as net cost or benefit over 'Scenario 1: No AWM'

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			COSTS (AUD) / year[4]			
			Surveillance	Eradication	Post-harvest	Difference
Scenario 3:	NSW	PFA	16806	~0	218529	201723
		FFEZ	0	~0	0	0
Current AWM		Total	16806	~0	218529	201723
Extent	VIC	PFA	17111	~0	392001	409112
		FFEZ	0	~0	0	0
Optimal Monitoring		Total	17111	~0	392001	409112
	Total	PFA	305	~0	610530	610835
		FFEZ	0	~0	0	0
		Total	305	~0	610530	610835

4. Red: cost; Black: benefit; calculated as net cost or benefit over 'Scenario 2: Current AWM

From the above BCA we can begin to value the possible benefits of new technologies that reduce costs (e.g., cheaper surveillance or post-harvest treatments). The value of these technologies will be different under different scenarios. For example, a 10% reduction in post-harvest treatments will reduce the annual net benefits of the AWM scheme by $3.4 million, but deliver a benefit of $10.7 million over the remainder of the FFEZ where post-harvest treatments are obligatory (benefits of such technologies outside of the FFEZ are ignored). As the total costs of surveillance and eradication are relatively low, a 10% reduction in the cost of these technologies will deliver only relatively marginal improvements. However, the benefits of these technologies tend to show high 'leverage': a reduction in surveillance cost can make it economic to surveil at a higher rate in critical production areas, thus delivering larger than expected benefits in terms of saved post-harvest treatments. That is, leverage exists whenever there is a synergistic 'knock-on' effect of a technology on other options in the AWM management mix.

Summary and Conclusion

The main findings from the Q-FAWM model are:

1. Total net benefits of the current Tri-State FFEZ strategy are $23.6 million per year, or 60% of the $39.3 million total potential savings of avoided post-harvest costs.

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2. The benefit of greater investment in surveillance is due to earlier detection, but the magnitude of this benefit varies over the year.
3. In the absence of any market regulation it is economically optimal to survey at the lowest possible level.
4. It is optimal to increase surveillance effort in high value production areas from the minimum rate of surveillance specified by market regulation, which defines a 'biosecurity constraint'. However, optimum trap spacing ranges between 700 and 1000 m.
5. The effect of a user-pays cost sharing arrangement is to increase surveillance when production value is high.
6. Savings due to a 10% reduction in the duration of outbreaks is less than savings on a 10% reduction in the probability of outbreak. Benefits of effective border control are higher during winter months than summer months.
7. The potential benefits from investing in improving post-harvest costs are far greater across the FFEZ than any other management strategy or technology thus far investigated. This has to be balanced against the likelihood of developing improved post harvest technology.

The minimum level of surveillance required by the current market regulation defines a biosecurity constraint, i.e., the minimum level of surveillance to ensure biosecure outcomes at the destination market. Decreasing the level of surveillance risks an increased probability of Qfly populations residing undetected in the landscape for extended period of time. It is this biosecurity risk, and its potential consequence in allowing exported produce to be both infested and untreated, that a 'biosecruity constraint' seeks to mitigate through an economically optimal mix of management options under an AWM scheme. Without the biosecurity constraint then trading partners will not engage in pest-free status trading, and the entire value of the FFEZ will be lost.

The Q-FAWM model has demonstrated the value achievable through marginal improvements in a select number of R&D and management options. In so doing, the Q-FAWM model has demonstrated the value of a bioeconomic, or disaggregated, approach to valuing R&D. Critically, it is the population ecology of the pest interacting with the AWM design that determines the biosecurity risk to export markets. It is thus up to the regulators to define, in these terms, the minimum acceptable level of risk before an evidence base can be provided to justify relaxing any of the current market regulations. However, as has been demonstrated, an evidence base can be provided to justify increasing surveillance heterogeneously across the Sunraysia PFA. Furthermore, if AWM managers believe that R&D outcomes can be achieved at less cost than their computed benefits (allowing for some discounting over time) then investment in R&D is supported. The natural extension of this work is, in having valued different R&D options, to determine an optimal portfolio of R&D investments given a fixed R&D budget constraint.

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Network Wide Management (NWM) of Stored Grain Biosecurity in Western Australia

The attributes of the biosecurity system suggest a four step bioeconomic spatial and temporal bioeconomic model GRANEWM. **Module 1**: ***Biosecurity Contract,*** based on the Cooperative Bulk Handling Ltd (CBH) BetterFarm IQ scheme (CBH, 2009), between the bulk handler and the farmer that ensures an optimal level of biosecurity effort by the farmer; **Module 2:** ***Farm to Receival*** represents profit maximizing allocations by the farm to receival sites; and **Module 3**: ***Receival to Port*** represents a least cost (transport and biosecurity cost) choice for delivering wheat to Kwinana. **Module 4:** ***Biosecurity Risk*** takes the distribution of grain from farm to port as given and assesses the risk of a biosecurity failure. Figure 22 below gives a schematic representation of how the modules represent the grain supply chain from farm to port.

Managing stored grain biosecurity (defined here as ensuring that grain is insect free for export) in the short term involves the effective use of phosphine fumigation, in particular for the management of stored grain on farm and through the CBH network. In the medium term there are implications for CBH storage assets as the prevalence of weak and strong resistance of grain beetles (Lesser Grain Borer Red, Rust Flour Beetle, Rice Weevil, Saw Tooth Grain Beetle, Flat Gain Beetle) to phosphine increases leading to a requirement that grain is fumigated in sealed stores. The situation in Western Australia is summarised by Chami et al (2011)

> *'The Western Australian stored grain industry is heavily reliant on phosphine to meet export market demand for insect and residue-free grain. The industry is threatened by phosphine resistance in grain insects due to the use of phosphine at all stages of the value chain, unrestricted use in poorly sealed storages and the lack of suitable alternatives. To preserve the life of phosphine, extension of responsible fumigation practices along with grain insect resistance monitoring and management has been conducted since 1984. Data show a slow increase in frequency of weak phosphine resistance but strong resistance has, until recently, only been detected in intercepted quarantine goods. The Western Australian focus is on monitoring to identify phosphine resistance, followed by effective treatment and eradication of strongly resistant strains.'*

The grain supply network in WA is currently at risk due to widespread weak phosphine resistance. Strong phosphine resistance has already been identified on two farms in WA (Chami et al., 2011) and this indicates that it could start to spread undetected throughout the WA grain supply network as it has in Eastern Australia. In the long term, the emergence of strong resistance will entail the introduction of alternative residue free fumigants such as nitrogen and carbon dioxide, but this would need to be linked to a significant investment in new storage facilities. Given the sunk investment costs in storage technology based on phosphine, the most cost efficient strategy for the medium term (the next ten to fifteen years) is likely to involve better use of existing infrastructure and more effective fumigation with phosphine at higher pressures in sealed stores. This may entail closing recieval stores and not accepting grain from farm stores that represent an excessive biosecurity risk.

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The spread of strong phosphine resistance in the Eastern States and is thought to be due to the misuse of phosphine on farm over a prolonged period. Newman (2010), in his review of the evolution of phosphine use in Western Australia identifies how resistance has probably emerged and the importance of phosphine to the grain industry in WA:

> *Phosphine has been available to famers since the 1950s when the label recommendations included the use of the product in unsealed storages and admixture to a grain stream. … It is suggested the continued use of phosphine in this manner for many decades in Australia has led to an escalating resistance in stored grain insects. In the 1980s CBH…created sealed storage in which to use phosphine exclusively for the protection of export grain. …placed more reliance on phosphine for the profitability of the entire grain storage industry in WA*. (Newman, 2010, p99)

In terms of economics and management, a three pronged strategy is considered. First, provide farmers with an incentive to deliver insect-free and residue-free grain to CBH stores; second, within CBH, use existing infrastructure to ensure that neither infestations nor resistance emerges and third develop monitoring methods that are able to identify outbreaks of strongly resistant grain beetles quickly and cheaply, and isolate and eradicate the outbreak (Newman, 2010).

The economic analysis of NWM outlined in Figure 22 has as its objective the minimization of the total cost to farmers and CBH. If CBH shuts a large number of grain stores additional costs shift to producers in the form of transport costs. Therefore costs are given for the supply from farms to port. On the one hand, if viewed as a monopoly (only provider of grain transport, storage and export facilities in WA), CBH would aim to maximise profits and would not allow access to receival sites with high handling cost grain (including biosecurity and transport cost). Instead, as a cooperative, CBH balances profit against the profitability of members. Thus an objective for CBH may be to maximise producer plus CBH profits (where producers as shareholders) benefit from CBH. The current contract is outlined in the Grain Operations Harvest Guide (CBH, 2010) which has two price levels one for tier 1 receival sites and another for tier 2.

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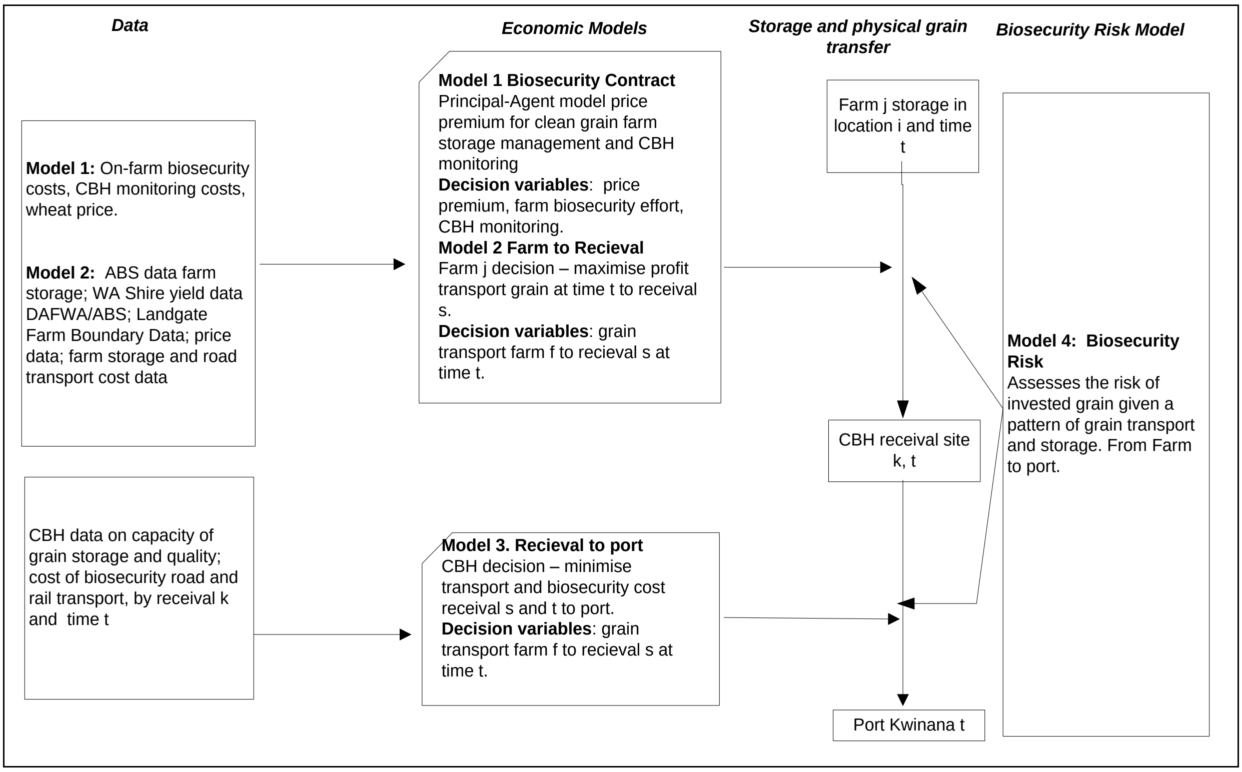

Figure 22. Modules for Network Wide Stored Grain Biosecurity Management

The modules are considered in turn. First the grain supply chain for the CBH Kwinana port zone has three steps: farm storage, receival site (including direct transfer to the Metro Grain Centre) and the port. The modules account for the spatial distribution of grain and the temporal allocation of grain through storage.

Module 1: *Biosecurity Contract*

The ability of a grain handler, such as CBH, to contract for grain that is insect and other contaminant free is complicated by twin problems of asymmetric information and moral hazard. Asymmetric information implies that the farmer knows how the grain has been managed in storage and at the farm, but CBH cannot observe this directly. The related problem of moral hazard is where the farmer does not have an incentive to manage stored grain according to industry best practice. There is widespread evidence from other CRC projects (CRC7009) that standards of stored grain management for biosecurity are not universally applied (Taylor and Slattery, 2010). The problem that CBH faces is one of a principal and an agent, where CBH devises a grain supply contract that pays producers a price premium for clean grain. Indirectly this induces the farmers to increase their biosecurity efforts on farm, but to reinforce this CBH must also engage in sampling for live insects and pests at the receival site. The mathematical form of the module is given in the Appendix (Grain Network Wide Management Modules 1 to 4). Table 5 gives the summary results. Data for this module are based on cost estimates for CBH monitoring and the cost of implementing best practice in terms of farm biosecurity management.

The results of this model give a clear message that asymmetric information reduces the profits of both the farm and CBH. New technology that reduces the cost of monitoring to

CBH is beneficial as it reduces CBH costs, but also induces a higher level of biosecurity effort by the farmer.

The results in Table 5 illustrate the information that the biosecurity contract module produces. CBH, as the principal offers a contract to a producer that includes a price premium, when clean grain is detected, fixes a level of monitoring of grain quality and targets a level of farm effort, and that entails labour and material costs related to managing biosecurity on farms.

Table 5. Results of the Biodiversity Contract Module (per tonne delivered)

Results	Index of farm biosecurity effort (e^f)	Index of CBH monitoring intensity (e^m)	Priice premium (θ)	CBH profit	Farmer Profit	Total profit
1. Perfect information	0.849	1	14.52	80.94	228.20	309.14
2. Non-verifiable farm effort CBH zero cost	0.732	1	13.65	79.77	228.20	307.97
3. Non-verifiable farm effort CBH monitoring costly	0.657	0.803	16.03	49.33	228.62E	277.95
4. Cooperative solution	0.945	0	0	81.25	210.32	291.57

An interesting aspect of these results is that asymmetric information, relating to grain quality and in particular the level of effort that the farmer applies to grain biosecurity management on farm imposes a cost on CBH. Consider the perfect information result (1) in this instance, CBH is able to detect infested grain costlessly and therefore selects the highest possible level of monitoring, e^m=1, also CBH is able to contract on a level of farm effort measured as an index where $e^f = 1$ is industry best practice. Results (2) and (3) shows the more realistic case that once CBH has to depend on a price premium θ (or cost discount) to provide producers with an incentive to deliver insect-free grain then the incentive for farm effort declines and this is especially the case in (3) when the cost of CBH monitoring dictates that CBH engages in imperfect monitoring and occasionally mis-classifies grain as infested (when not-infested) and vice-versa. These errors of classification reduce the incentives to producers for biosecurity effort. Some of the reduction in total profit can be recovered through a cooperative solution where the farmer ensures insect-free grain on farm and CBH does not engage in monitoring.

Module 2: ***Farm to Receival***

A farmer solves a straightforward profit maximizing problem in selecting the receival sites to allocate grain to. This involves estimating the road cost to the closest receival site and the prices paid at receival sites. There are approximately 5876 farms, and 233 receival stores at 114 receival sites. The farmer's optimization problem is of significance to the management of biosecurity as CBH can influence the movement of grain by

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adjusting charges at receival sites to reflect the full handling costs for receival sites. Therefore it can reduce deliveries to stores that are viewed as a higher biosecurity risk as they are unable to sustain effective phosphine fumigation.

The firm maximizes profit over three periods given an initial wheat harvest and a storage capacity. The average storage capacity is based on ABS data (ABS, 2010) for the average storage capacity of grain farms in Western Australia and is distributed to farms on the basis of a percentage of the crop. The mathematical form of the module is given in the Appendix.

Figure 23 shows the components of the GIS analysis to measure road distances from all farms to all receival sites. Figure 24 indicates the distribution of shire wheat yields. These yields are used, in conjunction with the Landgate farm boundary data, to estimate the wheat supply of all 5876 farms.

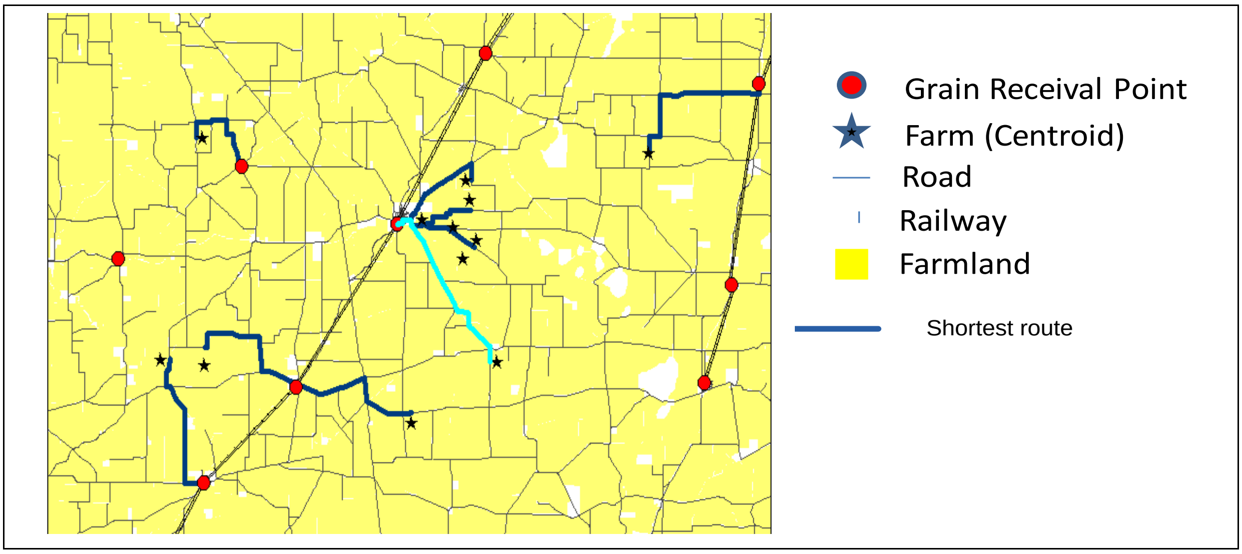
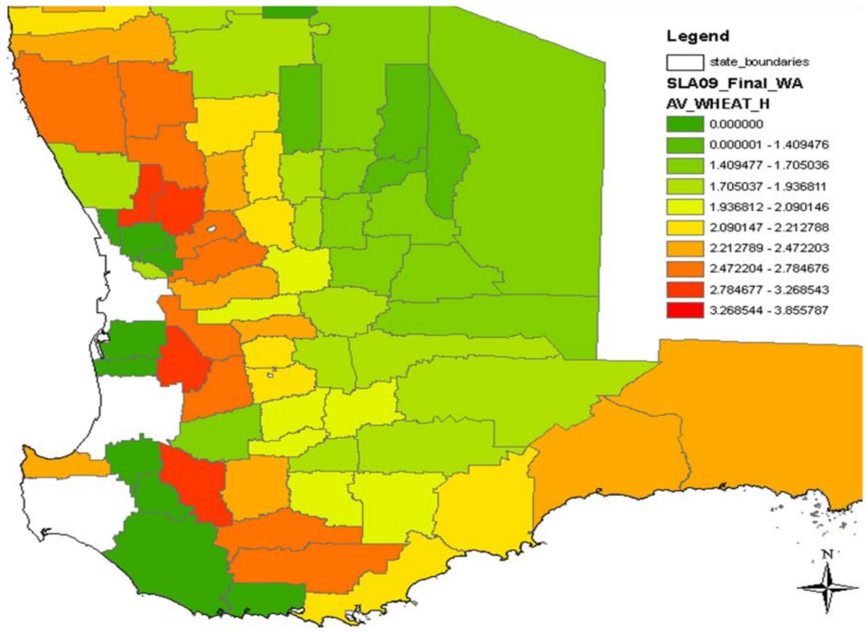


Figure 23. Corrigin Farm Example

Shows the Landgate farm centroids, railway lines, roads, and receival points. The bold blue lines give the shortest distance from one selected farm centroid to the nearest receival site.



Source DAFWA

Figure 24. Yield Distribution by Shires in WA

Module 3: *Receival to Port*

Figure 25 shows the location of receival sites and the rail network for the Kwinana zone. Module 3 finds a cost minimizing solution to a grain transport and storage over three periods within the supply network from receival to port. This module can simulate a range of biosecurity scenarios. For instance, a scenario of where sub-standard receival sites are closed when not suitable for fumigation (see Table 7 below). Other scenarios could include additional fumigations to eradicate insects from regions where strong resistance has been identified. Model 3 and Model 2 are run sequentially to evaluate scenarios. Model 2 gives the starting condition for Model 3 in terms of the grain delivered to receival sites in the different periods.

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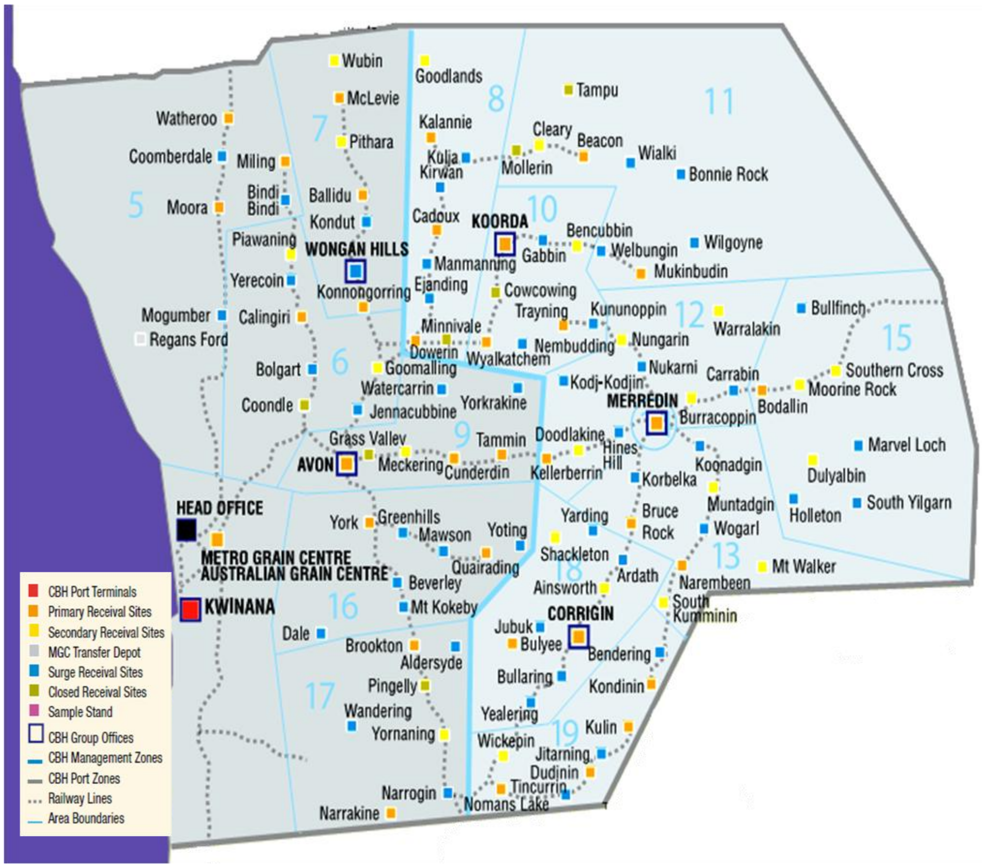

Figure 25. CBH grain receival sites in the Kwinana zone

Table 6 summarises the movement of grain from farm to receival sites and to Kwinana. The largest proportion of grain is stored in horizontal type storage (HOR, OBH, HRC and CIR). A subset of ten stores were defined as being in need of upgrading, and thereby represented a 'weak link' in ensuring insect free grain. Table 7 represents this scenario run through Module 2 (Farm to Receival) and Module 3 (Receival to Port). This has two opposing financial effects: it reduces farm profits slightly by increasing transport costs from farm to the receival site. For CBH it reduces the costs of running receival sites and also reduces transport costs to port. Thus closing receival sites shifts costs from CBH to producers. However in this instance it would pay CBH to compensate the producers affected as CBH's cost saving exceeds the loss of producer profit.

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Table 6. Wheat distribution in Kwinana Zone by storage and transport type (Model 3)

Receival – Sites	Bin Type	Peak Period (T1) in Tonnes (000s)	% of total	Storage Period (T2) in Tonnes (000s)	% of total
On Road	HOR	315.00	12%	160.35	12.79%
	OBH	364.00	13.43%	145.64	12%
	HRC	4.59	0.17%	2.37	0.19%
	SIL	16.04	0.59%	0.00	0%
	CIR	11.24	0%	0.00	0.00%
	Total	710.87	***26.50%***	308.36	***24.59%***
on Standard Gauge Rail	HOR	125.97	5%	0.00	0.00%
	OBH	159.89	6%	101.88	8%
	HRC	60.87	2%	0.00	0.00%
	SIL	1.34	0%	0.00	0%
	CIR	17.59	0.65%	17.59	1.40%
	Total	365.65	**13.50%**	119.47	**9.53%**
on Narrow Gauge Rail	HOR	723.31	26.69%	315.81	25%
	OBH	699.69	25.82%	449.88	36%
	HRC	40.65	1.50%	1.58	0%
	SIL	71.70	3%	25.52	2%
	CIR	98.35	3.63%	33.48	3%
	Total	1,633.70	**60%**	826.26	**65.89%**
Total Rail		1,999.35	***73.50%***	***945,730.35***	***75.41%***
Total Road and Rail		2,710.22	***100%***	**1,254,087.00**	***100%***

HOR horizontal storage; OBH horizontal storage; HRC large horizontal storage; SIL Silos; CIR Circular horizontal.

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Table 7. Change in farm profits and CBH costs ($ millions)

Model 2: Farm to Receival	Status quo 2008	After Closure	Difference	% Difference
Biosecurity cost	18.16	18.16	0	0.00
Transport cost	3.94	3.97	-0.0275	-0.70
Handling cost	16.41	16.41	0	0.00
Storage cost	3.27	3.27	0	0.00
Total Profits	995.01	994.97	0.04	0.00
Model 3: Receival to Port				
Biosecurity cost	0.34	0.36	-0.01424	-4.17
Transport cost	90.07	81.65	8.429	9.36
Handling cost	14.61	15.13	-0.529	-3.62
Storage cost	32.49	32.49	0	0.00
Total cost	137.51	129.62	7.88576	5.73

Module 4: *Biosecurity Risk*

The ***Biosecurity Risk*** model estimates the cost of infested grain when not treated at a receival site. The model calculates the cost of bad grain for different levels of farmers' biosecurity effort (i.e., the probability of the farmer delivering an infested parcel to a grain receival site; Figure 26). This cost function is then a component of the CBH's net benefit when contracting with farmers in the ***Biosecurity Contract*** model.

The ***Biosecurity Risk*** model uses as inputs the schedule of deliveries from each farms to each receival site in each time period from the ***Farm to Receival*** model, divided into 30 tonne 'truckloads'. The storage type of each receival store determines parcels are combined and placed in stores of different quality ('high', 'medium' and 'low'). These storage types are assigned probabilities of successful insect control through fumigation of individual parcels (0.99, 0.96 and 0.9 for storage types).

Bulked together, the probability of successful control within a storage type is dependent on the probability of parcel control, the size of the store and the rate that infested parcels are delivered (determined by the farmer's biosecurity effort). The ***Receival to Port*** model then passes information to the ***Biosecurity Risk*** model about how much of the grain received is then delivered to the port, and how much is carried over and stored at the receival node from one time period to another. In the ***Biosecuiry Risk*** model infested grain is then bulked again at the port from grain at different receival nodes, and from different storage types into 30000 tonne 'port' parcels. It is assumed that CBH has perfect knowledge of infested grain once delivered from the receival site to the port.

The probability of infested grain delivered by the farmer is defined for the first time period, and then doubled for each subsequent time period. A probability of infested grain on farm of greater than 0.1 leads to pest saturation of all bulk parcels at the port, requiring treatment of all grain at the port at a cost of 0.17 $/tonne.

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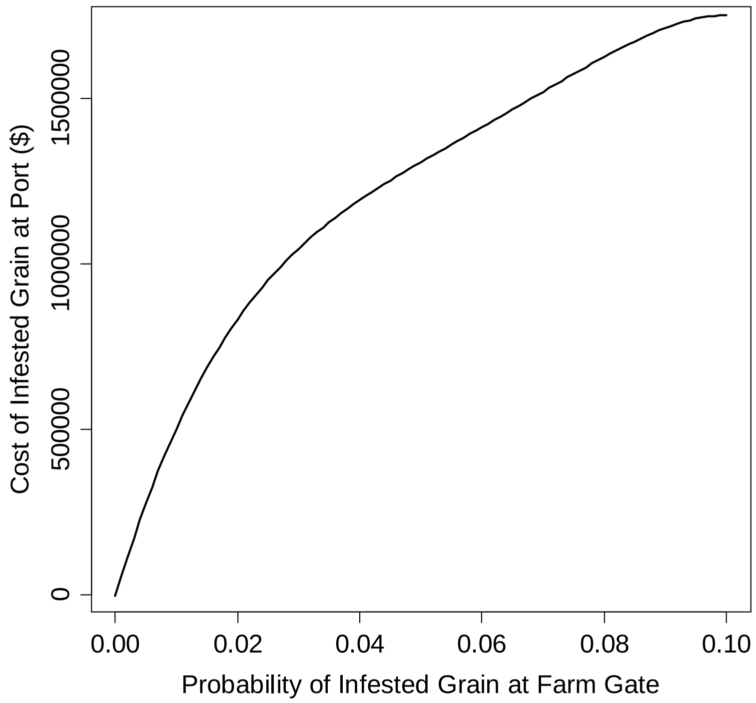

Figure 26. Bulk Costs of Ineffectively Treated Infested Grain at the Port for the Kwinana Network

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3. Implications for Stakeholders

The design of a strategic mix for Area- or Network-Wide Management requires implementation of a bioeconomic model describing pest behaviour and the processes of its transport and dispersal. For example, the Qfly model was modelled as a jump-diffusion process, with a probability of outbreak describing entry of the pest into the FFEZ and a local diffusion model of how unobserved populations interact with a surveillance grid. Similarly, the grain NWM associates a risk of infested grain with both truckload parcels of grain transported from farms to grain receival nodes, and bulk parcels transported down-stream from the receival nodes to the port. Consequently, heterogeneous storage at the nodes determined a spatially heterogeneous level of control of the infested grain parcels. Both frameworks report net social benefits, and hence constitute a benefit-cost analysis. However, as the design of AWM/NWM occurs at the level of management (i.e., how much to invest in each option of a portfolio of management options) the benefit-cost analysis is disaggregated through explicit modelling of behavioural responses of a biosecurity threat to changes in management. This is different from past BCAs of area freedom that present a small set of discrete scenarios to assist strategic policy choice, i.e., decisions are based on aggregated information. Critically, the design of the AWM is already decided on for each scenario by the time it reaches the policy maker, leaving little room for on-ground managers to adapt an AWM scheme to local production landscapes.

Economically optimal levels of investment in a management option can to an extent be determined even for difficult to value options, such as surveillance whose benefits are indirect and depend on the success of the AWM scheme as whole. In general, invest more in AWM management options where production value is greatest, and is at most risk of value loss. This is borne out in the marginally higher levels of optimal surveillance effort calculated for the Mildura region of the Sunraysia PFA, and when farmers will invest more in on-farm biosecurity in the presence of increased biosecurity surveillance and associated payment penalties from the bulk grain handler. Optimality then becomes a heterogeneous decision over time and space.

Implications for Qfly AWM

- It is economically optimal to undertake surveillance on a grid of sentinel surveillance points spaced 830 m apart. This implies that the current surveillance schedule of one trap every 1000 m in production areas and one trap every 400 m in residential areas largely satisfies economic criteria in addition to the biosecurity criteria.
- Due to the relatively low cost of postharvest treatments in the Sunraysia PFA then optimal surveillance differs little between regions. Only when the 'smoothed' production value is below $200/ha/yr is it economic to monitor at lower rates. However, if post-harvest costs increase significantly (say with the loss of chemical control options), or if monitoring costs decrease, then a greater level of spatial heterogeneity in optimal monitoring levels is realised. A doubling of post-harvest costs resulted in a surveillance effort of one trap every 320 m optimal for high

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production value areas in the Mildura region, following a simple sensitivity analysis.

- By far the greatest potential cost savings from R & D are to be realised from investments that reduce the cost of post-harvest treatments. This is because Qfly outbreaks are an intrinsic risk in the system, and that benefits of improved post-harvest treatment are realised over the whole of the FFEZ, rather than solely within the PFA. Improvements in surveillance will not ameliorate the intrinsic risk of outbreaks, only lessen their severity, as will improved eradication. The potential benefits of improved post-harvest treatment must be weighed against the likelihood of realising those benefits and other constraints such as health and safety.
- The cost of implementing AWM over the whole FFEZ region is more than offset by the post-harvest cost savings realised within the Sunraysia PFA, and confirms the findings of previous BCA of the Tri-State FFEZ strategy. However, there is significant risk of elevated incidence of Qfly outbreaks over decadal time scales, even in the absence of climate change, which will impact significantly on the profitability of the FFEZ scheme. To persist with AWM through these periods and to justify the public expense will likely be politically more difficult. However, even in the worst case scenarios the FFEZ scheme pays for itself, rather than incurring a net loss.

Implications for Grain NWM

- Contracts for grain delivery should have a clear incentive structure that rewards the delivery of insect free grain. The contract should have charges differentiated based on quality and biosecurity risk. Grain supplied from farm storage should be subject to additional sampling either on farm or at the receival site.
- Increasing the frequency of receival site monitoring or increasing its effectiveness through new technology to detect live insects and insect eggs is beneficial as it indirectly increases the level of biosecurity effort on farm. The lax biosecurity standards observed on farms are directly due to a lack of incentives and low rates of rejection due to insect contamination.
- Changes in the bulk handling network, for instance a receival site closure, should be assessed in terms of changes in producer profits and bulk handler costs. Thus, if overall there is a gain in profit from altering the inventory of storage facilities then a change in those facilities should be considered.
- More work needs to be done on a strategy for the emergence of strong resistance on WA farms. If a region develops strong resistance this implies that grain should probably move to a sealed storage at some point between farm and Kwinana.
- The current cost of infested grain not being detected until the port is relatively modest at a maximum of $1.5 million. This cost could easily double or quadruple with the onset of strong resistance if phosphine treatments are extended or alternative and more costly methods of treatment are required.
- Currently there is evidence that CBH can operate with some stores closed on the basis of fumigation standards and this would actually save CBH money. Farmers would incur a small additional transport cost.

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Future Directions for Prioritisation of R & D

A bioeconomic framework for evaluating R&D options has been provided in this project. In so doing the current constraints to a more comprehensive analysis of R&D investment have been identified:

1. Access to and availability of information for individual biosecurity case studies.
2. Complexity of the investment problem: due to project time constraints then not all R&D and management options could be rigorously evaluated. In some instances, such as the indirect benefits of the FFEZ as a buffer region to the Sunraysia (i.e., distance to the FFEZ boundary from the PFA boundary), the valuation of benefits will require more extensive bioeconomic modelling.
3. Risk of policy failure: a measure of ecological risk has been assigned to our BCA estimates but requires a significant investment in accurate bioeconomic modelling. For instance, postharvest treatment costs have a higher associated standard error than eradication costs in the PFA case study. These risk estimates are underestimated as they do not include estimates of parameter uncertainty in the underlying ecological models. However, these measures of the risk of policy failure (i.e., realisations of net loss,) need to be incorporated into the R&D prioritisation framework.
4. An assessment of the likelihood of each R&D project succeeding in delivering its outcomes needs to be estimated, alongside bioeconomic valuations of a project's potential benefits.
5. Optimising management strategies and market regulations may be just as important as R&D in delivering improved economic and biosecurity outcomes.

We are optimistic that these issues can be solved on a technical level. In so doing the current approach to valuation of various R&D and management or market regulation options can be generalised as a portfolio selection problem: select a mix of R&D and management options that best maximises returns at minimal risk of both policy failure and non-delivery of R&D. This 'risk-efficiency' framework was presented at the 2011 CRCNPB Science Exchange (Florec et al, 2011). The authors aim to implement the risk-efficiency framework in future work, potentially for both the Qfly AWM and grain NWM case studies.

A key notion of the risk-efficiency framework is that of 'strategic buckets' (Kavadias and Loch, 2004). For example, monitoring, eradication and postharvest treatment are different strategic investment buckets, that group by theme a number of different investment options. In this way specific R&D projects are aggregated into 'strategic buckets'. If a rationale for investment in one strategic bucket can be made over that for another then this sets the strategic direction of investment. Similarly, different biosecurity threats may be viewed as different strategic buckets: at a more aggregated level is it more important for the nation to invest in grain biosecurity as opposed to Qfly AWM, or similarly is there a mix of investments across the two industries that maximises returns yet minimises risk? The advantage of a disaggregated, or bioeconomic approach, is that in principle it can be aggregated up to the scale of policy decision making. However, a disaggregated approach entails a greater requirement for information and capacity for bioeconomic modelling. Furthermore, at the end of the modelling process there is likely to remain some key R&D and management options that are difficult to

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model explicitly and hence value, typically where benefits of those options are only indirectly realised.

Linkages with other CRCNPB projects

This project, as an investigation of R&D options, naturally links with many of the projects within the CRC for National Plant Biosecurity. Research projects whose outcomes could be represented by, and assist in improving upon, a disaggregated modelling approach are detailed here:

Early threat or quarantine risk analysis (CRC10001, CRC10010, and CRC10068) would equate to a probability model of the likelihood of population arrival or infestation of bulk good parcels (or other vector) for novel organisms.

Modelling projects CRC10073 and CRC10124 would provide readily accessible simulation tools and population model parameters for assessing the interaction of a novel or established pest with a specified surveillance network design.

DNA databases and taxonomy (CRC20055 and CRC20115) may in future be used to improve a probability of outbreak or infestation model by identifying source regions of invading populations, and hence provide a better understanding of the scale of population dispersal and associated risks and controls.

Biosensor detection of grain pests would provide grain handlers an increased ability to contract with farmers to improve on-farm biosecurity in an age when increasing number of farmers are storing increasing amounts of grain on-farm for market advantage (CRC20093).

Research on **phosphine resistance** would provide a better understanding of the costs of phosphine resistance, in addition to overall cost of managing biosecurity risks in a grain NWM, which could then be modelled in a spatially explicit manner (CRC20057 and CRC20080).

Findings from CRC40088 will help elucidate the role of **pre-harvest AWM strategies**, the benefits of which are not documented in this current report as they are largely unknown.

Many of the programmes in the **surveillance** stream will have a direct impact on bioeconomic models of surveillance, biosecurity contracts and interactions with the ecology of a biosecurity pest. Similarly, **post-harvest integrity** programmes will in particular influence the modelling of grain storage, pest detection, resistance to eradication controls, and the likelihood of successful control, and help determine the cost of potentially losing an important control such as phosphine in grain storage.

Capacity Building

We participated in Hazel Parry's BDemon population modelling group (Project 10071), linking population modellers with interests in biosecurity across Australia and south-east Asia. This has lead to Hazel Parry, Sama Low-Choy (CRCNPB), and Rohan Sadler co-organising a session on spatially explicit population modelling at the MODSIM conference, *Sustaining Our Future: Understanding and Living with Uncertainty*, 12-16 December 2011, Perth (Session E.16), with Eelke Jongejans (Radboud University, The Netherlands) as international invited speaker. Rohan Sadler has also facilitated the monthly EcoMod discussion group at the University of Western Australia for 2010-11, in support of CRCNPB postgraduate students (Hoda Abougamos CRCNPB 60128, Mingren Shi CRCNPB 60128, and David Savage CRC60076). Several meetings were also organised between Western Australian participants in the CRCNPB between industry (DAFWA) and researchers (UWA, Murdoch), with the help of Maria de Sousa-Majer (DAFWA; CRCNPB 10073).

Secondary Project Deliverables

- A spatio-temporal database of landscape and climatic factors for the whole of NSW and Victoria ready for the landscape modelling of Qfly has been compiled.

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- R software ports of the Climex software calculating climate indices from BOM data, and of a Qfly stage structured population model returning mean population growth rates from climate data is available.
- Extensive routines in R for processing the PestMon database have been developed.
- A framework for integrating the economics of surveillance into spatially explicit population models for Qfly.
- A set of inference methods for calibrating and estimating elements of the surveillance-population hybrid model from empirically observed Qfly captures to support evidenced-based policy.
- A surveillance cost calculator for Qfly monitoring (as an Excel spreadsheet).
- The bioeconomic model for Qfly can readily incorporate climate change scenarios in future.
- All the four modules of the GRANEWM model will be made available (GAMS code and R code), excluding any commercially sensitive data from CBH.

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4. Recommendations

Recommendations for Qfly AWM

These recommendations for Qfly AWM are couched in terms of what would best advance a bioeconomic approach to valuing and prioritising R&D under area- and network- wide management of biosecurity pests.

Recommendation 1. Estimation of time-varying population parameters for Qfly
For a rigorous, evidence-based bioeconomic approach to be implemented then key population parameters need to be estimated. Measures of parameter uncertainty need to be included to inform the decision maker of how uncertainty in the underlying ecological process propagates through the economic analysis for a reliable measure of risk of policy failure. This measure of risk of policy failure is key to valuing and prioritisation of future R&D. Furthermore, a *priori* knowledge of key system parameters such as the rate of Qfly capture by Lynfield traps will allow rapid economic assessment of AWM strategy options.

> **Recommendation 1a. Release-capture experiments**: BCA results are highly dependent on parameters of Qfly diffusion model. These parameters are largely uncertain. Release-capture data using SIT populations can help isolate time-varying rates of population dispersal, and inform how local landscape features (such as arrangement of orchards and timing of fruit production) facilitate or inhibit local population dispersal. This data is key to examining in detail how dispersing populations interact with surveillance grids. Such data should be readily available to biosecurity researchers, possibly under the aegis of BioSIRT.

Recommendation 2. Optimal Location of Surveillance Sentinels for Qfly Detection
While this work says something of optimal rates of surveillance, it says little of optimal location of sentinel traps. This facility location problem is known to be computationally hard, and is further complicated by a complex landscape mosaic of mixed land-uses. For instance, the contiguity of the landscape mosaic in terms of Qfly dispersal may be different at different spatial scales. The outcomes of any study of population parameters will assist in resolving this problem, and aid research projects seeking to improve surveillance effectiveness by adaptively changing surveillance effort both spatially and through time. Moreover, such knowledge would be useful to understanding the role and location of the FFEZ buffer area in reducing the probability of outbreak, which in this current study was confounded by other spatial variables.

Recommendation 3. Integrating all FFEZ Qfly trapping databases under BioSIRT
The lack of readily available Qfly trapping data was the critical limiting factor to advancing this project. Data for NSW was provided by Industry & Investment NSW, but full delivery of data was delayed until 15 months into a 23 month project (due to valid operational reasons, including demands on key staff from urgent biosecurity issues such as the locust plague and an exceptional year over 2010/2011 for Qfly outbreaks). Provision of the historical Victorian and South Australian Qfly trapping data, in conjunction with the NSW PestMon database, would greatly facilitate the extension of this model to more complex market scenarios, and improve the rigour of the bioeconomic model. The BioSIRT initiative would be an appropriate platform for the

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provision of that data, and protection for state agencies over market sensitive information. Provision of such data in a readily transferable format would greatly facilitate future researchers.

Recommendation 4. AWM and Climate Change
The Q-FAWM model may be readily extended in future work to consider future climate change scenarios, and what this means for the FFEZ strategy, as the dynamics of Qfly outbreaks is driven by Climex derived climate indices. Valuation of climate change mitigating strategies may be conducted.

Recommendation 5. Alternate Market Rules
A natural extension of the Q-FAWM model is to explore other market rules. The one generation rule for market recertification was utilised in this study as it led to a greater total number of outbreaks being declared, and more reliable modelling of both the distribution of outbreaks and their duration. The current analysis therefore underestimates post-harvest costs. Further data would be required to enable a more robust modelling of other market rules (one generation and 28 days, three generations, and different suspension zones for different markets), and options to alter market rules could be included within a risk-efficiency analysis (Recommendation 6).

Recommendation 6. R&D risk-efficiency analysis
A full risk-efficiency analysis of competing R&D options for both the Qfly AWM and grain NWM case studies would provide the first evidence-based treatment of research project selection under any CRC banner, and provide support to decision makers in rationalising R&D choices.

Recommendation 7: Size of eradication zone
The PestMon database can be queried to examine the probability of initially declared outbreaks resulting in further outbreaks being identified with the suspension zone, but external to the 1.5 km radius eradication zone (alongside the other BioSIRT databases on Qfly trapping). This unknown variable has key economic impacts as it results in the radius of the suspension zone being doubled, and hence the area of production subject to market loss being quadrupled.

Recommendations for Grain NWM

Recommendation 1: Monitoring for strong phosphine resistance
DAFWA and CBH should develop routine procedures of monitoring for strong phosphine resistance and an eradication strategy for when it is detected.

Recommendation 2: Close sub-standard stores
Phosphine is fundamental to the on-going functioning of the grain NWM and our recommendation is that bulk handlers should do more to safeguard its value. One pathway to safeguarding the value of phosophine is to close sub-standard grain stores at receival nodes, to protect the bulk grain movements from the weakest link in the grain NWM, i.e., on-farm storage. This would impose a small cost on producers and will likely save CBH money, in particular in the presence of phosphine resistance.

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Recommendation 3: Contingency plans for strong phosphine resistance
CBH should engage in modelling to assess the implications of managing regions with strongly resistant insects. This would imply that the large proportion of grain currently held in horizontal stores may, at some stage, need to be held in a sealed store for fumigation.

Recommendation 4: On-farm storage
The increased use of on farm storage is a concern especially as there is no binding accreditation scheme when currently there is widespread evidence of the misuse of phosphine. This should be addressed by a scheme such as Better Farm IQ tied to much stronger disincentives to deliver infested grain. This could include increased levels of grain pest monitoring by the bulk handler to which disincentives could be tied.

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5. Abbreviations/Glossary

ABBREVIATION	FULL TITLE
ABARE	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
AWM	Area-wide management
BCA	Benefit-cost analysis (alternatively CBA, or cost-benefit analysis)
BRS	Bureau of Rural Services
BioSIRT	Biosecurity Surveillance, Incident, Response and Tracing software
CBH	Cooperative Bulk Handling (Western Australia)
CRCNPB	Cooperative Research Centre for National Plant Biosecurity
DAFWA	Department of Agriculture and Food, Western Australia
DPI Victoria	Department of Primary Industries, Victoria
DSE Victoria	Department of Sustainability and the Environment, Victoria
FFEZ	Fruit fly exclusion zone (more specifically, the Tri-State Fruit Fly Exclusion Zone)
GAM	Generalised additive model
GAMS	Generalised Algebraic Model System (a software for solving decision problems)
GRANEWM	GRAin NEtwork Wide Management: the grain bioeconomic model developed here
I&I NSW	Industry and Investment, NSW
IPSM	International Phyto-Sanitary Management standards
LPMA	Land and Planning Management Authority, NSW
NFFWG	National Fruit Fly Working Group
NWM	Network wide management
PFA	Pest free area (typically the Sunraysia PFA)
Qfly	The Queensland fruit fly (*Bactrocera tyroni*)
Q-FAWM	Q-Fly AWM: the Qfly bioeconomic model developed here
R	A statistical computing and graphics software
R&D	Research and development
TSFFSSG	Tri-State Fruit Fly Strategy Steering Committee

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6. Plain English Website Summary

CRC project no:	CRC70100
Project title:	Optimal Investment in R&D for Plant Biosecurity
Project leader:	Ben White
Project team:	Rohan Sadler, Veronique Florec, Bernie Dominiak, Kirstopher Morey, Benjamin Buetre and Hoda Abougamous
Research outcomes:	The project has developed two detailed biosecurity models one for area wide management for Qfly in the Sunraysia Pest Free Area (PFA) and the other for Network Wide Management of stored grain pests in Western Australia. Both of these models can be used to address a wide range of biosecurity issues. Some examples are given below. The results from the Qfly analysis shows the benefits of the current PFA and the optimal investment in surveillance. In terms of R&D it is possible to assess the upper bounds of returns to investment in improved border control, surveillance and eradication technology. The stored grain analysis shows the costs of operating the grain supply network in the Kwinana zone and the costs to producers and the bulk handlers of closing sub-standard grain stores. The stored grain analysis shows that, in the absence of strong phosphine resistance, the cost of biosecurity lapses are relatively small so long as phosphine remains an effective fumigant.
Research implications:	• It is economically optimal to undertake surveillance on a grid of sentinel surveillance points spaced 830 m apart. This implies that the current surveillance schedule of one trap every 1000 m in production areas and one trap every 400 m in residential areas largely satisfies economic criteria in addition to the biosecurity criteria. • Optimal surveillance does not vary significantly across the PFA. • By far the greatest potential cost savings from R & D are to be realised from investments that reduce the cost of post-harvest treatments. This is because Qfly outbreaks are an intrinsic risk in the system, and that benefits of improved post-harvest treatment are realised over the whole of the FFEZ, rather than solely within the PFA. • The cost of implementing AWM over the whole FFEZ region is more than offset by the post-harvest cost savings realised within the Sunraysia PFA, and confirms the findings of previous BCA of the Tri-State FFEZ strategy. However, there is significant risk of elevated incidence of Qfly outbreaks over decadal time scales, even in the absence of climate change, which will impact significantly on the profitability of the FFEZ scheme. To persist with AWM through these

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	periods and to justify the public expense will likely be politically more difficult. However, even in the worst case scenarios the FFEZ scheme pays for itself, rather than incurring a net loss. **Implications for Grain NWM** • Contracts for grain delivery should have a clear incentive structure that rewards the delivery of insect free grain. • Increasing the frequency of receival site monitoring or increasing its effectiveness through new technology to detect live insects and insect eggs is beneficial as it indirectly increases the level of biosecutiy effort on farm. • Changes in the bulk handling network, for instance a receival site closure, should be assessed in terms of changes in producer profits and bulk handler costs. Thus if overall there is a gain in profit from altering the inventory of storage facilities then a change in those facilities should be considered. • The current cost of infested grain not being detected until the port is relatively modest at a maximum of $1.5 million.
Research publications: White[a] et al. Sadler[a] et al. Florec[a] et al. Sadler[b] et al. Abougamos et al. Sadler[c] et al.	**Peer-reviewed journal articles:** White B, RJ Sadler, V Florec, BC Dominiak. (forthcoming). An economic analysis of AWM for fruit flies in Australia. Target: *Australian Journal of Agricultural Economics*. Sadler RJ, V Florec, B White, BC Dominiak. (forthcoming). Empirical time to detection distributions for monitoring grids overlaying integro-difference population models. Target: *Journal of Mathematical Biology*. Florec V, B White, RJ Sadler, BC Dominiak. (forthcoming). An economic analysis of AWM for fruit flies in Australia. Target: *Food Policy*. Sadler RJ, V Florec, B White, BC Dominiak. (forthcoming). Risk of declaring outbreaks in the area-wide management of Queensland fruit fly (*Bactrocera tryoni*) across southeast Australia. Target: *Entomological Research*. Abougamos H, B White, RJ Sadler (forthcoming). Optimal biosecurity contracts in grain bulk handling. Target: *Australian Journal of Agricultural Science* **Peer-reviewed conference papers:** Sadler RJ, V Florec, B White, BC Dominiak. 2011. Calibrating a jump-diffusion model of an endemic invasive: Metamodels, statistics and Qfly. MODSIM 2011, Perth. **Book chapters:**

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Sadler[d] et al.	Sadler RJ, B White, V Florec, BC Dominiak (forthcoming). Valuing biosecurity monitoring under area-wide management: the Queensland fruit fly in south-eastern Australia. In Mengersen et al (eds). *Biosecurity Surveillance: A Practical Approach*.
	Reports:
Florec[b] et al.	Florec V, Sadler RJ, and B White. (2010). Cost Benefit Analysis of the Establishment and Maintenance of Fruit Fly Free Areas. Technical Report 1: Optimal Investment in R&D for Plant Biosecurity CRC 70100. Cooperative Research Centre for National Plant Biosecurity, Bruce, ACT. 4th February 2010. 42pp.
Florec[c] et al.	Florec V, Sadler RJ, and B White. (2010). An Economic Analysis of Surveillance for Area-Wide Management of Fruit Flies. Technical Report 2: Optimal Investment in R&D for Plant Biosecurity CRC 70100. Cooperative Research Centre for National Plant Biosecurity, Bruce, ACT. 24th August 2010. 15pp.
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Morey and Millist	Morey K, N Millist (2011). Market Access Recovery Following a Fruit Fly Outbreak. ABARES Report to The University of Western Australia, November 2011, Draft, Canberra.
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	Abougamos HRA (2012). *An Economic Analysis of Surveillance and Quality Assurance as Strategies to Maintain Grain Market Access*. Thesis, Doctor of Philosophy, The University of Western Australia, Perth.
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APPENDIX: Grain Network Wide Management Models

Module1 Biosecurity Contract

The grain merchant (CBH) procures grain from a group of identical farmers. The aim of CBH is to maximise profit from selling grain to the world market at price p_w less biosecurity costs. CBH's expected costs depend on the level effort exerted by the producer to deliver clean grain, monitoring costs for CBH and the price premium paid to provide an incentive for providing clean grain.

The module is developed in two stages. The first version of the module has the farmer's effort as non-verifiable, but CBH are able to identify the status of the grain (either infested or insect free) without cost. This module is further modified to show the case where CBH can contract directly for biosecurity effort.

Non-verifiable effort and perfect information

The merchant's objective function is given by the expected net margin per tonne of grain:

$$Z = \max_{0 \le e^f \le 1, \theta \ge 0,} \{ p_w - (e^f(1+\theta)p_f + (1-e^f)p_f + (1-e^f)c^b) \} \qquad \text{(A1.1)}$$

Where e^f is the farmer's effort in storing and treating grain in a way that minimizes the probability of infestation. It is convenient to define the effort index $0 \le e^f \le 1$ as the probability of grain being insect free (Laffont and Martimort, 2002, p168). The price p_f is the reserve value of grain to the farmer when grain is sold to the domestic market or used on farm as seed or livestock feed. The variable θ gives the price premium if the grain is clean, the term c^b is the cost of treating infested grain. The farmer's incentive to apply effort depends on the profit derived from selling grain to CBH. This constraint comes in two parts a participation constraint that assesses that profit is not reduced from selling to CBH:

$$e^f(1+\theta)p_f + (1-e^f)p_f - c_f\,(e^f) \ge 0 \qquad \text{(A1.2)}$$

and an incentive constraint, that assesses if the marginal benefit of exerting effort exceeds marginal costs. As the incentive constraint (Laffont and Martimont, 2002, p195) implies the participation constraint we only consider the former, the farmer's effort is non-verifiable:

$$(\theta)p_f - c_f'(e^f) \ge 0$$
(A1.3)

where $c_f'(e^f)$ is the marginal cost of biosecurity effort. The assumptions on the cost function are that: $c_f'(e^f) > 0, c_f''(e^f) > 0, c_f'''(e^f) > 0$.

If the merchants objective function is maximized subject to (2) we obtain the first order condition:

$$\theta = (c^b - ec_f''(e^f))/p_f \qquad \text{(A1.4)}$$

Substituting this back into the incentive constraint (2) yields an equation for the optimal effort:

$$\left(c^b - c_f'(e^f) - e^f c_f''(e^f)\right) = 0 \qquad \text{(A1.5)}$$

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Verifiable effort

If the merchant is able observe effort, they would contract for an optimal level of effort and pay the farmer the reserve price, p_f. The necessary condition is:

$$\left(c^b - c_f'\left(e^f\right)\right) = 0$$

Non-verifiable effort implies a higher optimal effort than the first-best.

Non-verifiable effort and imperfect and costly CBH monitoring

In this module set up we consider the realistic situation where the farmer effort is non-verifiable and the CBH engages in costly monitoring. There now a number of possibilities summarised in Table A1.1

Table A1.1 Event Table

	CBH detects grain status	
Farm biosecurity state	Detected	Not detected
Insect free	$e^f e^m$	$e^f(1-e^m)$
Infested	$(1-e^f)e^m$	$(1-e^f)(1-e^m)$

$$Z = \max_{0\le e^f\le 1, 0\le e^m \le 1, \theta\ge 0,}\{p_w - (\alpha^s(e^f,e^m)(1+\theta)p_f + \left(1-\alpha^s(e^f,e^m)\right)p_f + c^b(e^f,e^m) + c^m(e^m)\}$$

Where the probability of paying the premium is $\alpha^s(e^f,e^m) = e^f e^m + (1-e^f)(1-e^m)$ The expected cost of bad grain $c^b(e^f,e^m) = (1-e^f)e^m c_0^b + (1-e^f)(1-e^m)c_1^b$. The first term is the expected cost when infested grain is detected and has to be segregated, the second term is the expected cost when infested grain is not detected and is allowed to infest a batch of grain. It is expected that: $c_1^b > c_0^b$.

Subject to the incentive constraint:

$$\alpha_{e^f}^s \theta p_f - c_f'(e^f) \ge 0$$

Where variables as subscripts indicate partial derivatives, for instance $\alpha_{e^f}^s$. The condition for an optimal selection of biosecurity effort between the farm and the monitoring effort on the part of the merchant is given by:

$$\frac{c_{e^m}^b + c'(e^m)}{c_{e^f}^b - h(e^f,e^m)c_f''(e^f)} = \frac{\left(\alpha_{e^m}^s + 2\,h(e^f,e^m)\right)}{(\alpha_{e^f}^s)}$$

Where $h(e^f,e^m) = -(\alpha^s(e^f,e^m)/\alpha_{e^f}^s)$. That is the marginal expected cost of infested grain equals the corresponding increase in the probability of grain being assessed as 'clean'.

For a given monitoring scheme for the merchants, the farmer exerts the following effort:

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$$\left(-c^{b}_{e^f} - c_f'(e^f) - h(e^f, e^m)c_f''(e^f)\right) = 0$$

Parameter values for the module

The module has a relatively small number of parameters most are straightforward, such as the WA wheat price. The price of rejected grain or infested grain is set as a parameter in relation to the WA price. The only non-linear elements in the module are the costs of farm effort and the costs of CBH monitoring. These functions are calibrated from available data (Taylor and Dibley, 2009, CRC70096).

The cost of infested grain involves two terms: when infested grain is identified, then it can be separated and treated at a relatively low cost. However a more substantial cost is incurred when infested grain is not detected and is combined in a larger batch.

Table A1 Module 1 Parameters

Parameter or function	Value or function	units
p_w export wheat price 2008	326	\$ per tonne
p^f farmer's reserve wheat prize	$0.7\, p_w$	\$ per tonne
$c_f\ (e^f) = \beta_0 \left(\frac{1}{1-e^f}\right)^{\beta_1}$	$\beta_0 = 6.17;\ \beta_1 = 0.365961;$	\$ per tonne
$c_m(e^m) = \phi_0 \left(\frac{1}{1-e^m}\right)^{\phi_1}$	$\phi_0 = 10;\ \phi_1 = 0.5;$	\$ per tonne
$c_0\ , c_1$	$c_0 = 30, c_1 = 120$	\$ per tonne

The module is solved using non-linear programming, the relevant aspect of this module is the interaction between farm effort and CBH monitoring. Results are given in Table 3.2.1 in the main text.

Module 2 Farm to Receival

The aim of this module is twofold: first to predict farmer wheat allocations, spatially and over three periods based on profit maximization and second to estimate farmer welfare by estimating profit of wheat supply as the price paid less transport and biosecurity charges.

The module includes aggregates profit across 5876 farms and provides a starting value for grain allocated to 233 storage facilities at 114 receival sites. This includes a distinction between storage of different type at the same receival site (horizontal, vertical, silo, bunkers). Unless otherwise stated the source of costs and parameter values was CBH.

The linear programming module objective function is to:

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$$Maximise \sum_s \sum_t \sum_f \left(p_{st}^w - c_{stf}^m - c_{stf}^h \right) q_{stf} - \sum_t \sum_f \left(c_{tf}^c + c_{tf}^b \right) q_{tf}^c$$

Where *there are s* receival sites, *t storage periods and f* farms. Variable definitions are below. This objective is subject to an initial quantity of wheat constraint at time $t = 0$:

$$q_{0f} = a_f y_f ;$$

and a stored grain on farm constraint over the two storage periods:

$$q_{1f}^c = q_{0f} - \sum_s q_{s1f} ; \qquad q_{2f}^c = q_{1f}^c - \sum_s q_{s2f} \ \forall f ;$$

An on-farm storage capacity constraint:

$$q_{1f}^c \le q_f^{max} \ \forall f ;$$

Not that this only needs to apply in the first storage period. A constraint on the available storage at each receival point is then:

$$\sum_f q_{stf} \le q_{st}^{max} \ \forall s, t$$

Table A2 Module 2 variable definitions

Variable	**Definition**	**Comment**
q_{stf}	Quantity transported from farm *f* to receival store *s* at time *t=1,2,3*	
p_{st}^w	Price paid for grain delivered at site *s* during period *t* net of any delivery and service charges. Accounts for expected price increases.	
c_{stf}^m	Cost per tonne of transporting grain from farm *f* to store *s* in time *t*	Estimated from GIS distance estimates from farm centroid to receival store. [Road data source: Landgate].
c_{stf}^h	Cost per tonne of handling grain from farm *f* to store *s* in time *t*	
c_{tf}^c	Farm costs of storage per tonne. Includes interest foregone for one period.	
c_{tf}^b	Farm biosecurity cost of carrying one tonne of grain over a single period.	

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q_{tf}^{c}	Tonnes of grain stored on farm *f* in period *t.*	
q_{f}^{max}	Storage capacity on farm *f* in tonnes.	ABS estimate.
q_{st}^{max}	Storage capacity at receival store *s* at time *t*.	
$a_f y_f$	Initial harvest as area of wheat planted a_f times yield per ha y_f	Based on shire crop areas and shire yields [Source: ABS 2008]. Farm sizes and location given by unlabelled property ownership data [Source: DAFWA]. Bushland areas excised from properties to give arable land [Source: BRS/ DAFWA].

Module 3 Receival to Port

The ***Receival to Port*** *(Kwinana)* model gives the least cost transportation of wheat from receival to ship in Kwinana accounting for transport, storage and biosecurity management. Transport is by road, narrow gauge rail and standard gauge rail. The transport of grain is from 233 receival stores located on 114 receival sites. This allows a disaggregated analysis of the implications of closing grain stores and restricting the use of particular types of storage if an outbreak of phosphine resistant grain beetles reduces the ability of unsealed grain stores to ensure effective fumigation.

Cost minimization

$$Minimize \sum_{s}\sum_{t}\left(c_{st}^{ms}Q_{st} + \left(c_{st}^{cs} + c_{st}^{bs}\right)Q_{st}^{c}\right)$$

Subject to

$$Q_{st}^{c} = \sum_{f} q_{stf} - Q_{st} + Q_{t-1,s}^{c} \quad t = 2,3$$

$$Q_{st} \le Q_{st}^{max}$$

$$Q_{st}^{c} \le Q_{st}^{cmax}$$

$$\sum_{s} Q_{st} \le Q_{t}^{kmax} \forall t$$

Table A3 module 3 variable definition

Variable	Definition	Comment

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Q_{st}	Quantity transported from store *s* to Kwinana at time *t=1,2,3*	
Q^{c}_{st}	Quantity stored in tonnes at *s* in period *t*	
Q^{c}_{t-1s}	Quantity stored in the previous period	
Q^{max}_{st}	Road and rail maximum at s in time *t*	
Q^{cmax}_{st}	Storage maximum at *s* in time *t*.	
Q^{Kmax}_{t}	Maximum capacity at Kwinana in period *t*	
c^{ms}_{st}	Transport cost per tonne on road or rail.	
c^{cs}_{st}	Handling cost per tonne at store *s at* time *t*	
c^{bs}_{st}	Biosecurity cost per tonne at store *s* at time *t.*	