Baseline 'Consequence Measures' for Australia from the Torres Strait Islands Pathway to Queensland: Papaya Fruit Fly, Citrus Canker and Rabies

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Executive Summary

One of Australia's comparative advantages in international agricultural markets is the provision of premium produce from a clean agricultural environment, with relatively low levels of pests and diseases. Biosecurity measures have generally provided an essential protection for industry, the population, animals and the environment against the incursion of exotic pests and diseases, which could cause major health concerns and considerable economic damages. A key biosecurity pathway of special interest is the Torres Strait Islands, which borders northern Queensland. Among the principal pathways for pests and diseases are movements of people in boats, cargo shipments and environmental conditions, such as wind patterns and weather effects.

This report provides baseline 'consequence measures' for three case studies of invasive species of concern: papaya fruit fly, citrus canker and rabies. Consequence measures are given based on all available (albeit, in some cases limited) data and knowledge of the characteristics and risks of each pest or disease. The consequence measures take as given the current biosecurity protocols in the Torres Strait Islands and provide estimates of damages with existing control or response measures throughout. In other words, the consequence measures provide expected damages from an incursion with current settings, and are thus useful for calibrating a cost-benefit analysis, portfolio allocation models and Bayesian network models where probability values and specific alternative control measures condition the final outcome of a pest or disease spread.

Papaya Fruit Fly. The Asian papaya fruit fly *(Bactrocera papayae)* (PFF) is a serious pest worldwide. It is native to and widespread in South-East Asia and endemic in Papua New Guinea since 1992. In Australia, PFF was detected near Cairns in October 1995 and was successfully eradicated. However, the cost of eradication was significant at roughly $34 million, taking four years to eradicate the pest. The risk of a PFF outbreak is likely to be increasing given the increased movements in people and goods, and is thus an important threat to host agricultural industries in Queensland, currently valued in the billions of dollars.

In 2013–14, the total gross value of production of potential PFF host farms/industries in Queensland was roughly $1.15 billion. Bananas are the most important agricultural commodity in the state, accounting for $456 million and $407 million of the gross value of production (GVP) and farm gate value respectively (at 35 per cent of total GVP of PFF host farms/industries in QLD). Other important commodities include tomatoes, avocados, mandarins, and strawberries, contributing a GVP of $218.1, $112.8, $78.2 and $71.6 million in 2013, respectively. Capsicums, mangoes and apples are also important, at a GVP of $59.2, $53.2 and $45.2 million, respectively (Australian Bureau of Statistics (ABS 2014a).

The major horticultural areas, which are under a potential threat from PFF are the Wet Tropic region, the Burnett Mary region, the Burdekin region, the Border Rivers Naranoa–Balonne, the Southwest, the Fitzroy and the Northern region. There were about 2000 potential PFF host farms located in QLD in 2013. Farm size (measured in terms of gross value and farm gate value) varies greatly by commodity and area. As a result, the potential cost caused by PFF also varies significantly by region and commodity.

This section of the report provides two model frameworks. The first constructs a spatial stochastic dynamic model and uses a Sample Average Approximation (SAA) approach to predict damages and solve for optimal surveillance measures, accounting for all of the costs of a possible incursion and spread of PFF, including the cost of the surveillance program itself. Using a new optimization technique, in a novel way, this approach determines the best grid size to detect PFF early. Our method captures far more detail than the aggregate approach to these problems and is more efficient than basic simulation approaches at finding an optimal outcome. The results indicate a grid size of less than 1 km is best, suggesting that not enough resources for biosecurity are being directed to this activity in Queensland.

The second approach uses a more basic model where spatial maps, relevant parameter values and a logistic growth function are used to locate farms and simulate the spread and resulting damages from PFF. There are no optimal measures here, just a basic (more aggregated) simulation of potential damages. Estimated results indicate that the average (nominal) potential cost per year in Queensland caused by a PFF incursion and spread is $16.1 million. The total net present value of the potential cost of PFF (over 25 years) is estimated to range from $214.3 million to $250.0 million, with an average of $231.9 million (with a 90 per cent confidence interval). The cost of PFF is most significant for the Wet Tropic areas ($6.7 million dollars per year), followed by Burnett Mary ($4.3 million per year) and the Border Rivers Naranoa-Balone area ($2.2 million per year). The potential cost of PFF to the banana industry is the largest at about $88 million over 25 years, or 38 per cent of the state's total cost incurred as a result of a PFF spread.

Citrus Canker. The spread of citrus canker (*xanthomonas campestris*) (CC) would have multiple damaging effects on the citrus industry, including yield losses and significant losses in market access internationally. The loss in market access results in lower prices for fresh fruit sold domestically compared to premium (export) markets, along with lower prices overseas. Citrus is an important industry in Queensland, providing $81 million dollars in gross value of production in 2013–14 (ABS 2014a). The establishment and spread of citrus canker would cost citrus growers in this state considerably. The eradication cost of the Emerald (Queensland) outbreak was estimated to be roughly $26.8 million (Senate Standing Committees on Rural and Regional Affair and Transport, 2009. In this report, applying a spatial bioeconomic model, the most likely potential costs of citrus canker are estimated over a period of 15 years at $82 million and $91 million for Queensland and New South Wales, respectively. On average, the potential cost of a citrus canker spread and establishment is estimated to be $6.9 million and $5.5 million per year for Queensland and New South Wales. The potential cost of CC is most important for the Burnett Mary region (Queensland) and the Riverina (New South Wales).

Rabies. Rabies is a zoonosis caused by the rabies virus of the genus Lyssavirus *(Rhabdoviridae)*. The disease is one of the more serious public health diseases in the world, resulting in more than 55,000 deaths per year. Australia is currently free of rabies. However, given that rabies in present in Indonesia, with proximity to the Torres Strait Islands and Australia, the risk of rabies reaching northern Australia is increasing.

There are no fully developed risk assessments for the threat of rabies, although a principal threat is assumed to occur with wildlife and feral animals, and dogs are seen as the principal reservoir of the rabies virus. This report focuses on a rabid dogs analysis, including preliminary estimates of mass dog vaccination costs and other potential costs of a rabies outbreak.

For rabies in Australia, the cost of mass dog vaccinations is estimated to be $5.9 million, $8.5 million, $7.7 million and $5.8 million for Queensland, NSW, Victoria and South Australia, respectively. For the case of rabies outbreak (without an eradication strategy), the average cost of Post Exposure Treatment (PET) treatments per year is estimated to be $3.8 million, $6.0 million, $4.7 million and $1.3 for Queensland, NSW, Victoria and South Australia. Damages to livestock range from $45,000 to $200,000 per year, and vary by state.

Introduction

Biosecurity measures have provided an essential protection against the incursion of exotic pests and diseases, thus protecting both consumers and producers from major health concerns and guarding against pest and disease incursions that can potentially destroy local agricultural production. A key biosecurity pathway of special interest is the Torres Strait Islands, which borders northern Queensland. Among the principal pathways for pests and diseases in this region are movements of people in boats, cargo shipments and environmental conditions, such as wind patterns and weather effects. This report provides baseline 'consequence measures' for three case studies of invasive species of concern: papaya fruit fly, citrus canker and rabies. Consequence measures are given based on all available (albeit, in some cases limited) data and knowledge of the characteristics of each pest or disease. The consequence measures take as given the current biosecurity protocols in the Torres Strait Islands and provide estimates of damages with existing control or response measures throughout. In other words, the consequence measures provide expected damages from an incursion with current settings, and are thus useful for calibrating cost-benefit analysis, portfolio allocation models and Bayesian network models where probability values and specific alternative control measures condition the final outcome of a pest or disease spread.

The Asian papaya fruit fly *(Bactrocera papayae)* is a serious pest worldwide. It is native to and widespread in South-East Asia, including Thailand, Malaysia, Singapore, Brunei, Indonesia, East Timor and Papua New Guinea. Papaya fruit fly is endemic in Thailand, Malaysia, Borneo, Indonesia and Singapore and it has been present in Papua New Guinea since 1992. In March 1993, it was detected for the first time in Australian territory on the islands of Saibai, Boigu and Dauan, adjacent to the Papua New Guinea coast, and on Stephen and Darnley Islands close to the centre of the Torres Strait. Papaya fruit fly (PFF) has a number of potential pathways into the Torres Strait with monsoonal winds each wet season being one of the most likely. PFF is eradicated annually as part of a proactive containment strategy administered by Biosecurity Queensland and the Commonwealth Department of Agriculture (2015). On the mainland, PFF was first detected near Cairns in October 1995 and was successfully eradicated in 1999. The pest originated from 35 host species during the outbreak in Queensland, causing significant economic loss and costs associated with pest management. In total, the eradication of PFF in the 1995 outbreak cost over $34 million and it took four years (1995–99) to eradicate the pest.

Citrus canker (*xanthomonas campestris*) (CC) is a highly contagious bacterial disease of citrus trees and related varieties, including grapefruit, lemons, limes and oranges. It reduces the growth of new fruit and spoils healthy fruit. The disease affects any part of the citrus tree growing above the ground, producing warty, rust-brown spots (cankers) on the leaves, twigs, shoots and the fruit of citrus trees (Department of Agriculture and Fisheries of Queensland (DAF) 2015). Growth of young trees can be severely affected due to damage to new shoots (Quarantine of South Australia 2013). According to Dewdney and Graham (2014), major citrus canker outbreaks generally occur when new shoots are emerging or when fruit are in the early stages of development, especially if a major rainfall event occurs during this critical time. Frequent rainfall in warm weather, especially with storms, contributes to disease development. Citrus canker is mostly a 'cosmetic disease', but at high contamination levels the disease can cause defoliation, shoot die-back, and fruit drop. The outbreak of CC in Brazil was estimated to cost US$476 million dollars (Bassanezi et al 2009).

Rabies is a zoonosis caused by the rabies virus of the genus Lyssavirus *(Rhabdoviridae)*. The disease, which affects the central nervous system and is usually fatal, is a potential threat to more than 3.3 billion people worldwide (Tenzin 2012, Kaplin et al. 1986 and World Health Organisation (WHO) 2010). Rabies is one of the more serious public health diseases in the world, resulting in more than 55,000 deaths per year by rabid dogs. Almost all of these deaths occur in the rural areas of Asia and Africa (Knobel et. al 2005). The risk of rabies reaching northern Australia is increasing as the disease spreads to nearby areas. During the past 10 to 15 years, rabies has spread to areas of eastern Indonesia that were previously rabies-free, including Flores and Bali (Ward 2012), and is now present within 350 kilometres of northern Australia (Ward 2014). If rabies reaches Australia, it will have substantial adverse ecological, public health, economic and social impacts.

Baseline consequence measures for the three case studies, papaya fruit fly, citrus canker and rabies, follow. Concluding remarks provide a summary of the key results. There is some necessary repetition of content and results for readers who prefer to look at each specific case study separately.

1 Papaya Fruit Fly

For over 18 years, *The Long Term Containment Strategy for Exotic Fruit Flies in the Torres Strait*, which provides preventive measures against the establishment and spread of PFF, has been successful in protecting Australian horticulture from exotic fruit fly pests (Plant Health Committee 2013). There is no doubt that the potential benefit of preventive measures against PFF is significant. A recent study by ABARES (2013), provided a benefit-cost analysis for the long term containment and eradication strategy for exotic fruit flies in the Torres Strait. By incorporating the full range of horticultural industries potentially affected, the potential losses to producers and consumers from an exotic fruit fly incursion in mainland far north Queensland, spreading to the rest of Australia, were estimated at $2.1 billion and $1.2 billion, respectively (ABARES 2013). These large damages stem, in part, from aggregating results across various pests, producers, consumers and related industries and across all states, and an assumed time horizon for the estimation period (from one outbreak to the next) of 100 years. While this is an important contribution, our study focuses more narrowly on PFF, a principal threat in Queensland, with geographically-defined effects to local industry, over a much shorter time horizon. Spatial spread and density measures, along with specific damages to farms/industry in a spatial calibration, provides an added level of precision for estimating consequences from a potential PFF incursion.

1.1 Background of threat of papaya fruit fly in Queensland

1.1.1 Risk of papaya fruit fly in Torres Straight

Over 250 species of fruit flies in the family *Tephritidae* are present in Australia, but only ten are considered to be pests. Some fruit fly pests are endemic in Australia. For example, an endemic fruit fly of major concern in New South Wales is the Queensland fruit fly (QFF) (*Bactrocera tryoni*). QFF is native to eastern Queensland and northeastern New South Wales, and has spread to urban and horticultural areas in Queensland, New South Wales, Victoria and the Northern Territory (Department of Primary Industries (DPI) of New South Wales 2015).

Of special added concern, is the permanent, native population of the exotic pest fruit fly species in the Western Province of Papua New Guinea, immediately adjacent to the Torres Strait islands, posing a serious risk of a PFF outbreak in the Northern Territory and QLD, areas important for horticulture in Australia. Pests are normally thought to move into the Torres Strait by natural means, such as by wind currents, but also through human assisted pathways such as vessel movements and unauthorised foreign fishing activity. Like most tropical fruit fly species, PFF multiplies rapidly and can disperse over large distances. It is capable of establishing in any of the mainland states of Australia (Department of Agriculture and Fisheries (DAF) of Queensland 2015).

As a result of this threat, there are significant PFF preventive measures in place. According to the Department of Agriculture (2015), identifying and assessing the risk of PFF is essential for managing the pest in the Torres Strait, before they can become established and have a major impact on trade and production on the mainland. The Commonwealth Department of Agriculture is responsible for PFF surveillance on each inhabited island in the Torres Strait. Early detection of this pest greatly enhances the likelihood that the pest can be eradicated. For over 18 years, as mentioned, *The Long Term Containment Strategy for Exotic Fruit Flies in the Torres Strait* has been successful in protecting Australian horticulture from exotic fruit fly pests (Department of Agriculture 2015). Biosecurity Queensland also monitors a network of traps for PFF in high-risk urban and remote centres in Queensland, and has planned responses to any potential incursion.

Overall, there is a significant threat of PFF incursion to mainland Australia. Over the past ten years, there were at least 373 incidences of PFF detected in Torres Strait Zones, and preventive measures have been in place to prevent a PFF spread to Australia's mainland (see Table 1) (Plant Health Committee 2013).

Table 1: Preventive measures for exotic fruit flies in the Torres Strait Fruit Fly Strategy, 2002/03 to 2011/12

Year	Number of detections			Preventive measures		
	PFF	Melon fly	New Guinea fly	No. of detected traps	No. of islands bait sprayed	No. of islands blocked *
2002–03	100	0	32	42	7	8
2003–04	54	1	17	35	11	7
2004–05	53	0	4	8	8	8
2005–06	21	2	2	32	8	4
2006–07	49	0	40	9	6	5
2007–08	10	0	1	4	4	4
2008–09	5	0	0	3	3	4
2009–10	42	1	6	20	7	4
2010–11	0	0	3	3	4	4
2011–12	39	1	17	37	6	4
Total	373	5	122	193	61	52

*Source: Plant Health Committee (2013) based on Northern Australia Quarantine Strategy (NAQS). Note: * Male annihilation involves mass trapping using male lures to reduce fly males for monitoring PFF growth.*

1.1.2 Potential PFF host industries in Queensland

Table 2 provides the key facts for potential PFF host farms/industries in Queensland. Based on the Australian Bureau of Statistics (ABS) (2014a), the total gross value of production for PFF host farms/industries in Queensland was about $1.15 billion in 2012–13. Bananas are the most important agricultural commodity, by far, accounting for $456 million and $407 million of the gross value of production (GVP) and farm gate value respectively (or about 35.3 per cent of total GVP for PFF host farms/industries in QLD). The other important commodities are tomatoes, avocado, mandarin, and strawberries, contributing a GVP of $218.1, $112.8, $78.2

and \$71.6 million in 2013, respectively (see Table 2). Capsicums, mangoes and apples are also important, with a GVP of \$59.2, \$53.2 and \$45.2 million, respectively.

Table 2: Production and value of PFF host industries in Queensland, 2012–13

Commodity	Production	Number of farms	GVP	Local value
	(tons)	*(no)*	*(\$mill)*	*(\$mill)*
Avocados	29,582.4	330.4	111.8	94.2
Cherries	17.1	4.3	0.1	0.1
Mangoes	25,139.0	493.4	53.2	44.8
Nectarines	1,474.4	64.0	3.0	2.4
Peaches	1,355.6	89.0	2.3	1.8
Apples	34,002.2	44.6	45.2	37.6
Mandarins	55,461.9	115.7	78.2	64.7
Oranges	4,621.0	103.4	3.2	2.4
Pears (including Nashi)	343.6	15.7	0.6	0.5
Bananas	308,039.7	298.5	456.5	407.2
Strawberries	13,998.3	111.6	71.6	60.9
Grapes	1,507.3	97.5	50.6	45.2
Capsicums	22,587.3	102.2	59.2	49.3
Tomatoes	107,277.4	179.7	218.1	181.4
Total	605,407.1	2,050.0	1,153.5	992.6

Source: Australian Bureau Statistics, 2014a,b.

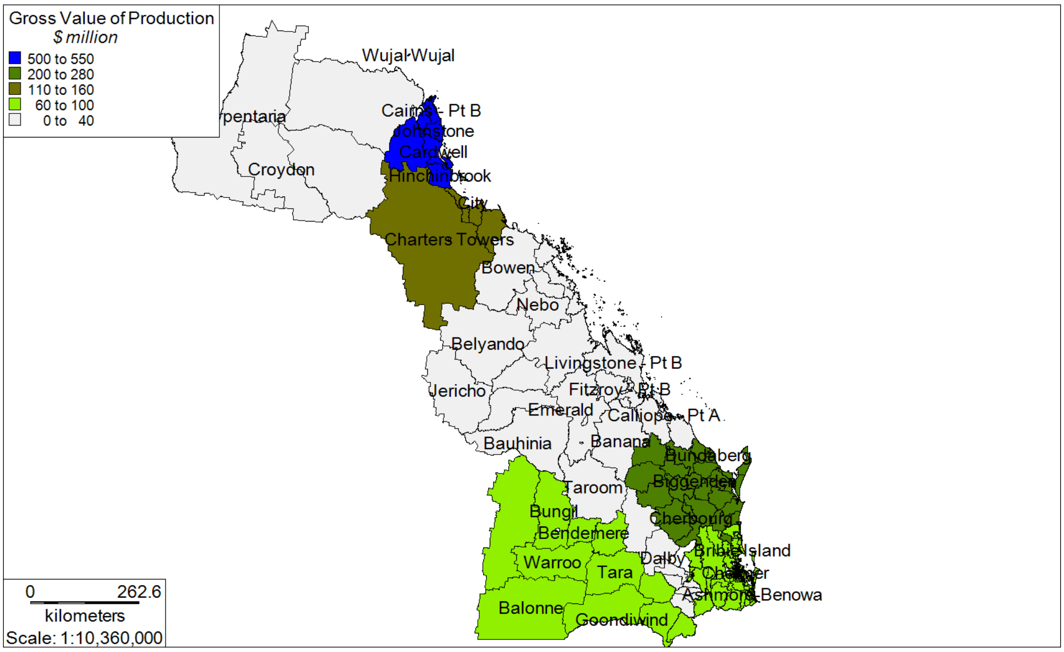
Figure 1 maps the areas of a high likelihood of potential PFF host farms/industries in QLD by the gross value production (GVP) in 2012–13. The major horticultural areas, which are under a potential threat of PFF, are the Wet Tropic region, the Burnett Mary region, the Burdekin region, the Border Rivers Naranoa–Balonne, the Southwest, the Fitzroy and the Northern region. There were about 2000 farms that are potential hosts for PFF located in QLD in 2012–13. The farm size (measured in terms of GVP and farm gate value) varies significantly by commodity and area (Figure 2).

In particular, there is a large variation in terms of average farm gate value from region to region, ranging from roughly \$80,000 to more than \$1 million in 2012–13 (see Figure 2). The average farm gate value in the Wet Tropic region and the Burdekin is about \$1 million, and much smaller, or about \$140,000–\$160,000, in the Northern Gulf and the Condamine regions. Farm size also varies significantly by commodities in a region. For example, in the Burdekin region, average farm gate value is about \$6 million for tomatoes farms, but is only about \$120,000 for mango farms. In the Wet Tropic region, average farm gate value is about \$1.7 million for banana farms and \$120,000 for mango farms.

1.2 Model 1: Optimal surveillance measures against PFF

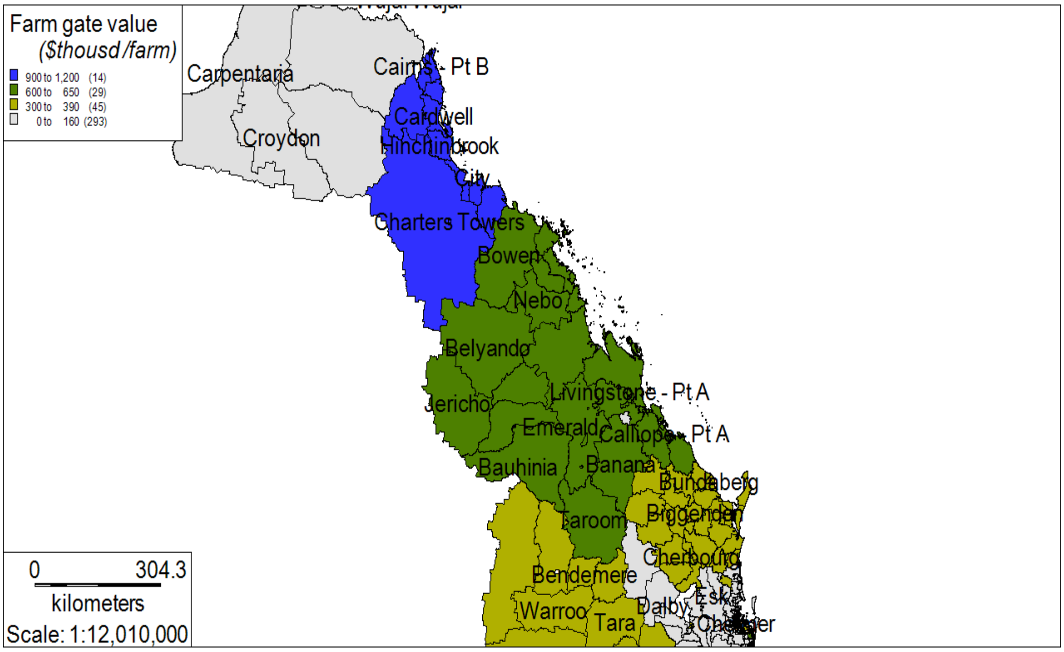
Prevention and control are the first line of defence against an alien invasive species (AIS) (Olsen at al., 2006), such as PFF. However, spending on prevention and control alone is not economically effective, since: (a) complete prevention has often proven to be impossible and prevention measures, no matter how stringent they are, can not keep up with the increasing risks of a bio-invasion due to globalisation (NISC, 2008) and new or enhanced environmental pathways; and (b) although the chance of a successful invasion by an AIS is often small (Williamson, 1996),

Figure 1: Gross value production in potential PFF host areas *($mill)*



Source: Australian Bureau of Statistics (ABS), 2014a.

Figure 2: Average farm gate value in potential PFF host areas (*$'000/farm)*



Source: Australian Bureau of Statistics (ABS), 2014a.

these threats, once established, are usually very expensive if not impossible to control unless their presence is detected early (Sinden et al., 2004; Clark and Weems Jr., 1988). For these reasons, early detection and rapid response (EDRR), the second line of defence, has attracted considerable attention over the last decade, with a particular focus on the trade-off that exists between the early detection of an AIS and the future cost of controlling it (Mehta et al. 2007).

The challenge of finding an optimal early detection point or the correct surveillance level depends on the economics of the problem and how an AIS invades and spreads. In general, there is a good deal of uncertainty over the likelihood of a incursion, its spread in terms of spatial and temporal characteristics and the potential economic damages that might occur, especially in cases where non-market values must be calculated. The model context is also necessarily large in this case, and fully and explicitly considering time, space, uncertainty and variability in economic damages in an optimisation problem quickly leads to a 'the curse of dimensionality' (Bellman 2003) and computational failure.

This section of the report develops an optimal surveillance model for fruit flies, a major threat to horticultural crops in many parts of the world. Finding an optimal surveillance measure against this type of AIS is particularly challenging. Not only do fruit flies disperse quickly and randomly in a local environment, and also over long distances, these threats have a rate and direction of dispersal that is highly dependent on time and environmental factors (Yanow and Sutherest, 1998). One of the biggest challenges in this class of problems is the possibility of the numerous contacts that fruit flies can make throughout their life cycle and the fact that it is impossible to fully trace and contain them locally, much less over large distances.

To examine all of the complications that go with time, spatial heterogeneity, uncertainty and the variability of economic damages explicitly, we design a stochastic spatial dynamic model, of very large dimension, to characterise the entry, spread and establishment of fruit flies in a local environment, and then combine it with an optimisation model that ensures that expenditures on surveillance for early detection are optimal. To do so, we use a Sample Average Approximation (SAA) approach to handle the dimensional complications and solve specifically for an optimal surveillance measure in terms of the number and size of trap grids to ensure early detection. As an example of the methodology we, of course, apply the model to a possible entry of Asian Papaya Fruit Fly (PFF) (*Bactrocera papayae*) in the state of Queensland, Victoria.

1.2.1 Related Literature

As mentioned, taking time, space and uncertainty into full account in an optimisation routine is generally limited by the curse of dimensionality. To make the problem manageable, early studies on optimal surveillance against an invasive threat often reduced the problem to one or two dimensions, with spatial heterogeneity either ignored (e.g. Mehta et al., 2007; Bogich et al., 2008), or largely reduced in dimension (Sharov, 2004; Ding et al., 2007; Finnoff et al., 2010a; Blackwood et al., 2010; Sanchirico et al., 2010; Gramig and Horan, 2011). Since an AIS spread is highly dependent on spatial heterogeneity, this 'aggregate' approach can produce misleading results (Wilen, 2007; Albers et al., 2010; Meentemeyer et al., 2012). As a second alternative, some studies opt to ignore the time dimension and thus optimise surveillance effort at a single point in time (Hauser and McCarthy, 2009; Horie et al., 2013). While providing useful insights, this approach may generate solutions that are not optimal for the entire time path, or across a heterogeneous spatial dimension, and it ignores solutions for a steady state which is reached slowly or never can be attained (Finnoff et al., 2010b). A third approach to AIS modelling (Epanchin-Niell and Wilen, 2012), is to explicitly model both time and space, but in a deterministic setting, thereby no longer allowing for fully articulated surveillance problems where uncertainty over spread, space and time matters.

For the spread of most invasive species, time, spatial characteristics, uncertainty and variability in damages all play important roles that should not be ignored. For this reason, the literature on trans-boundary animal diseases (TADs), and for some plant diseases, relies mostly on simulations, without an optimisation routine, to fully and explicitly model all of these dimensions (Morris et al., 2001; Ferguson et al., 2001; Tomassen et al., 2002; Keeling et al., 2003; Tildesley et al., 2006; Ward et al., 2009; Hayama et al., 2013; Atallah et al., 2014; Adeva et al., 2012). Simulations, however, reveal only the relative efficiency of one or at best a limited number of policy choices. More recently, a simulation-based optimisation approach has been suggested in applications to TADs to help keep the spatial dimension manageable by capturing only the 'average' movements for these threats over space (Kobayashi et al., 2007; Kompas, Ha, Nguyen, Garner, East and Roche, 2015). While providing useful insights, this quasi-aggregate approach still misses some spatial heterogeneity in spread patterns, especially with regard to the estimation of transmission coefficients.

Due to the large size of optimal surveillance problems, Kompas, Ha, Nguyen and Garner (2015) proposed the use of SAA in surveillance optimisation problems for TADs. Having desirable asymptotic statistical properties, SAA solves stochastic dynamic problems by using a combination of exterior sampling and deterministic optimisation methods (Shapiro et al., 2014; Shapiro, 2003; Verweij et al., 2003). To make SAA amenable to surveillance problems for TADs, Kompas, Ha, Nguyen and Garner (2015) design an infection tree model focusing on infection paths and use it with a combination of sensible "pruning" of the tree and parallel processing techniques to reduce dimension. However, this innovation is not directly applicable to surveillance problems for AIS, such as fruit flies, since: (a) these species make numerous contacts throughout their entire lives, thereby making the proposed infection tree in Kompas, Ha, Nguyen and Garner (2015) infeasible to build; and (b) they largely cannot be traced or contained, making any pruning rules difficult. Given these modelling challenges, the literature on optimal surveillance against fruit flies is scant and largely ignores the spatial dimension (Pierre, 2007; Kompas and Che, 2009; Florec et al., 2013). We solve this problem with an adaptation of the SAA approach, while still retaining a high resolution GIS map and complex spatial and time dimensions.

1.2.2 Methodology

In this section, we design a spatial stochastic dynamic model to characterise PFF movement. Our modelling setup is a combination of a meta-population model and a dispersal model. With QLD's GIS raster map, we divided our research area into smaller 'hospitable' patches or cells, where the flies settle into one (or more) of the cells, beginning in the far north of QLD. As the fly population grows, flies will start to depart (in various directions) in search for new patches and hosts, thus threatening an otherwise substantial horticultural industry both in Queensland and in other states in Australia. This model, in combination with our SAA approach, will be used to solve for the optimal surveillance measure for PFF.

1.2.3 Spatial modelling and surveillance

Space is the first component of our model. We pay special attention to local spatial heterogeneity, using a 50 by 50 metre raster map for QLD published by ABARES (2015). The high resolution map not only allows us to model the spread of fruit flies in greater detail for every region in QLD, but it also provides us with more flexibility in the biological modelling by allowing us to ignore within cell population growth. With an area of a cell being only 250m^2, in other words, we can effectively classify each cell as simply infected or not, without causing sizeable errors for the economic modelling.

In terms of local heterogeneity, there are 6 broad categories of land use in the raster map, with up to as many as 60 different smaller land use purposes in each category. In our study, a PFF incursion matters only in horticultural areas, with over a half of million rasters cells of this type in Queensland alone. The remaining 1.4 billion cells are classified as non-hospitable areas.

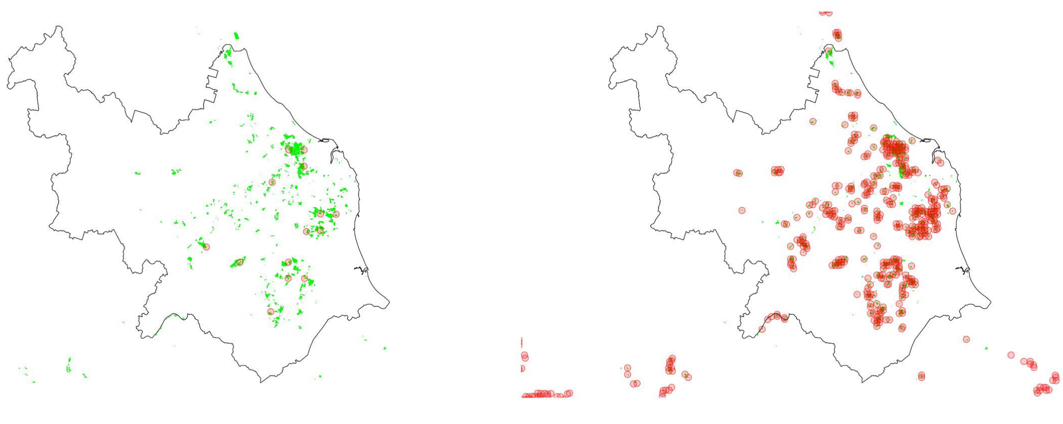
We calculate the production value for each cell in the raster map to help determine economic costs and benefits. The GIS data indicates that in some cases a raster cell can be categorised as specific to citrus and grape growing areas, but the majority of cells can only be designated by 'general horticultural use', given by perennial, seasonal, irrigated perennial, irrigated seasonal, and intensive horticulture. For each general horticultural use we approximate annual production revenue for a cell by dividing the corresponding horticultural production revenue, drawn from ABS (2015) data, across the appropriate cells. For the remainder of the other uses we use their revenue shares to adjust their cell values.

Another aspect of spatial modelling is surveillance grid design. As food is the primary reason for PFF migration, it is desirable that we place traps in the neighbourhood of a horticultural area. In our model, we divide our research area into a grid-space where we put a single trap in a grid cell if the horticultural area in that cell takes more than 10% of the total area. Since the cells are sufficiently small, we simply place the trap in a raster cell closest to the center of the defined grid. Figure 3 shows an example of simulated trap locations in Bundaberg, one of Queensland's local and more important horticultural regions. The green dots are horticultural raster cells, and the red circle denotes the trap location and a 500m 'sensitive area' surrounding the traps. Figure 3a shows the trap location for 5km trap grid (roughly equivalent to the current trap surveillance grid, when employed, in Queensland, see Kompas and Che, 2009) and Figure 3b simulates a much denser 1km trap surveillance grid. It is clear from the figures that the 1km surveillance trap grid is much more effective than the 5km trap grid in terms of coverage. However, the denser the surveillance grid, the more expensive it is. Our exercise is to determine optimal grid size, generating the best return on investment.

Figure 3: Simulation of the surveillance grid in Queensland's Bundaberg region.

(a) With 5 km trap grid

(b) With 1 km trap grid



1.2.4 Biological Modelling

Up to ten different life stages for PFF have been identified: from egg, larva, pupa to adult stages (see Yonow et al., 2004). For our modelling purposes, we are concerned only with two stages: (a) the early development stage (egg, larva, pupa), when the (would be) flies stay 'latent' at the host and (b) the adult (teneral and post-teneral) stage where flies can potentially reproduce, and more importantly migrate to other hosts and pass the outbreak on. Yonow et al., 2004 identified temperature and soil moisture as the two most important factors that can affect the longevity of flies at each stage of their life. Bateman (1967) studied the survival of PFF in various locations in Australia. His study shows that with a temperature ranging from 20–30^{o}C, it takes from 20–34 days for an egg to become pupal, and that the longevity of an adult fly ranges from 45–175 days, with lower temperatures associated with higher longevity.

As the population expands, part of the fly population will form 'departing propagules' in a search for new habitable hosts. Citing current literature, Adeva et al. (2012) identified dispersal as a key factor in the process of population stabilisation in heterogeneous space, or when predation or lack of food causes local extinction. Adeva et al. (2012) also identified two important factors in the dispersal process, which we will also focus in our work: (a) the speed of population spread over a suitable environment, and (b) the dispersal distance range.

In our approach, we do not model within patch population growth, instead we pay more attention to spatial heterogeneity. In order to do so, we again assume that a (habitable) patch or host can be identified as infected or not. If infected, it can release Π propagules (or fly clusters) at every unit of time after 4 weeks from the point of infection. The four week period is designed to take into account the early development period. After 4 weeks, adult flies emerge and they are ready to migrate. Also, given the points made above, we assume the propagules can live up to 10 weeks (the medium life span of an adult fly), during which they search for a new host to colonise.

Following Adeva et al. (2012), we identify two important factors in the process of propagule dispersal, range and direction. For traveling distance, Adeva et al. (2012) shows a diminishing dispersal distribution with 60% of the fly population rarely going further than 100m from their source of origin, 20% of the flies dispersing within (0.1,5]km, and the rest will make a long journey, up to 80km away. It is also clear the younger flies tend to fly much further than older flies, and flies 2-3 weeks old generally travel less than 200m a day. We adopt all these parameter values, as given by Adeva et al. (2012) , with the exception of the longest distance travelled. In our model, we choose a more conservative longest distance travelled of 94km, following a review by Dominiak (2012).

The second factor in the dispersal process is direction. Following Adeva et al. (2012), we assume that the flies can sense nearby suitable hosts. The probability of a fly to finding nearby host by proximity is given by Equation 1:

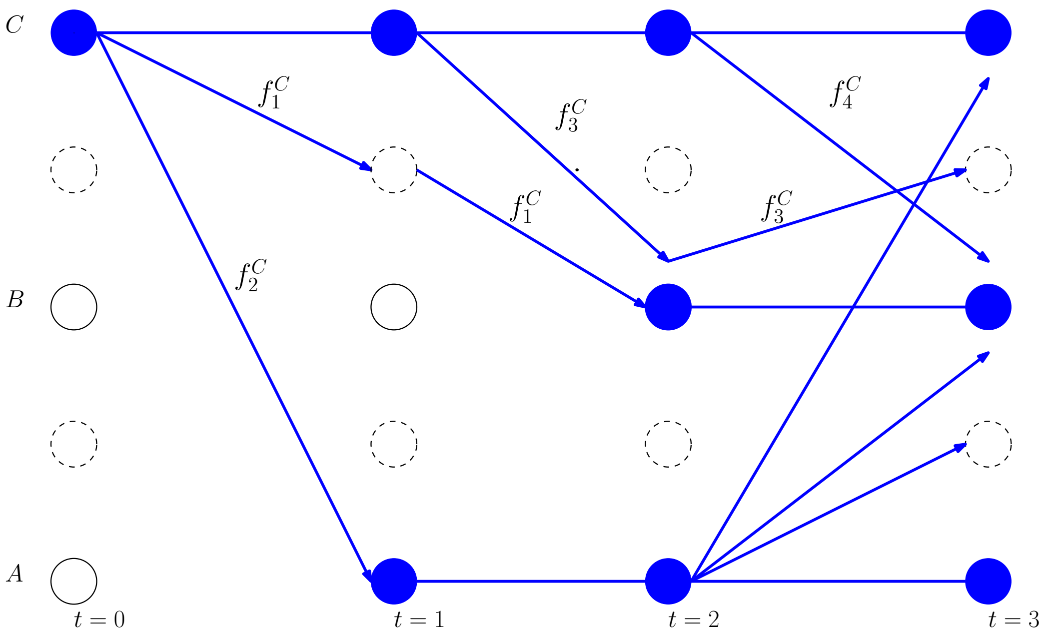
$$P(d) = \begin{cases} 0.0512987d^3 + 0.334853d^2 - 0.904237d + 1.08341 & if\ d\ \leq\ 3 \\ 0 & if\ d\ >\ 3 \end{cases} \tag{1}$$

where P is the probability of a host detection, and d is the distance from the host. Equation 1 ensures that the fly will detect a host within 0.1 km with certainty.

Given the travelling proclivities of flies, we assume two travelling types: an initial jump and an adjustment process. In the first week of their 10 week lifespan, when they are strong and active, the flies (or propagules) can choose to jump in any direction to a location between (0,94]km. We assume the probability for a propagule to make a jump is approximately 30%. The remaining 70% stay in the neighbourhood, and move locally. After a jump, the adjustment process begins. In the adjustment process, the propagules will choose a random direction and sense if there is a nearby host within reachable (one week flying) distance. If they do not find a host, they will fly randomly to any place within reachable distance, which is 1.4km for one week in our case. The stochastic nature of our model is dictated by the above jump and adjustment processes: they are both random. The flies, who find the host can stay and infest the area. The others will continue their search.

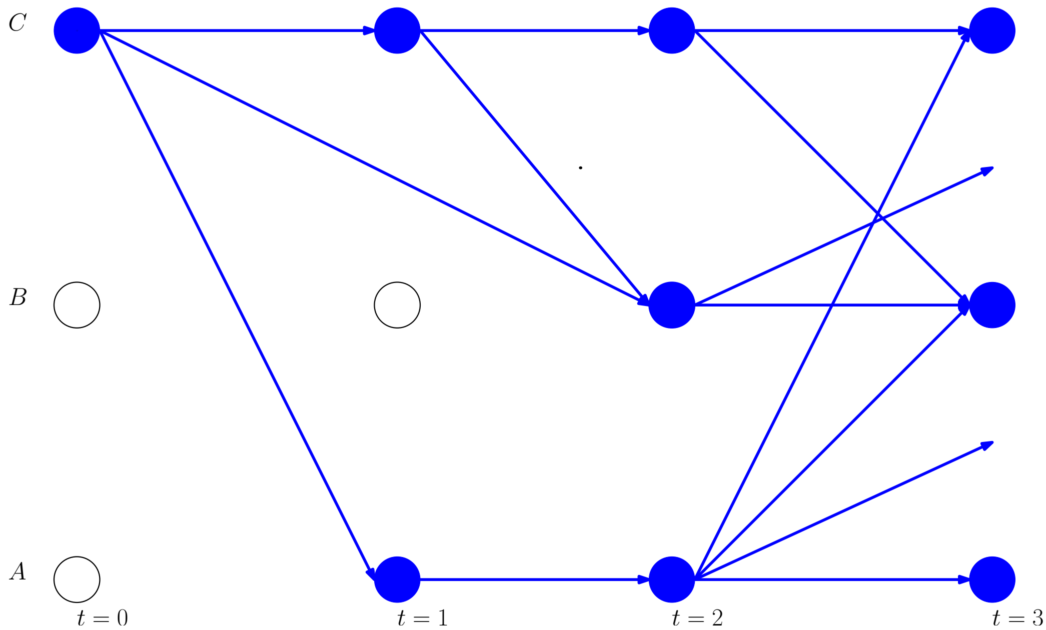
The dispersal process in our model can be represented in an extended network form (see Figure 4), where all the raster cells in our research area can be classified into habitable (solid circle) and a non-habitable (broken line circle) cells. An infected host (C) makes contact (infection) with other hosts via releasing flies. The flies can find a new host within one period (f_2^C), or they can jump to a random and non-habitable location and continue to search until finding a new host (f_1^C). If the host has been occupied before, the flies will depart immediately from it and continue their search for a new host in the next period (f_3^C). To that extent, our model can be seen as an extended network model where a node can contact other nodes through time (with fly longevity as the upper limit).

Figure 4: Network model for PFF case.



To simplify the model, let us hide the non-habitable nodes (consider them as hidden) and invalid connections (from un-infected host to an infected host). Our model can then be represented as a more standard extended network model, where any layer of nodes at particular time t can contact multiple adjacent (by time) layers (see Figure 5).

Figure 5: Network model for PFF case without hidden nodes and connections.



Denote A as the average age of adult flies. Without making matters too complicated, we take Y_t as the vector of all infected hosts at t, and assume Y_t will be a function of past infected hosts and present and past realisations of random dispersal events (ξ), our prior information. In addition, we assume that with a surveillance grid (d), the flies in a cell will be detected at some point, either by a trap or by passive detection, or what might be termed a 'natural detection point', typically by visual inspection of the fruit without the use of a trap (p). In any case, flies in detected cells will be treated and removed, hence the cell will stop releasing new flies and infecting others, so that the current infection status for Y_t will be a function of past infection status, surveillance and a natural detection point:

$$Y_t(Y_{t-1}...Y_{t-A}, \xi_{t-1}...\xi_{t-A}, d, p) = f(Y_{t-1}...Y_{t-A}, \xi_t, \xi_{t-1}...\xi_{t-A}, d, \tau) \tag{2}$$

where, without loss of generality, $Y_t(\Xi_t, Y_0, d, \tau)$, where Ξ_t is the past information matrix up to t and Y_0 is some initial point. We can also discard Y_0, to simplify notation, as it can be understood that the initial condition is a prerequisite for a solution to Equation 2. As such, Equation 2 thus governs the expansion of the fly population over time and heterogeneous space.

1.2.5 Meteorological model

Yonow et al. (2004) identifies temperature and soil moisture as important factors governing fly longevity at every stage of the life cycle. In addition, Dominiak et al., (2003), has indicated that winds of more than 4 km/h can redistribute fly populations. Therefore, we can not ignore the meteorological impact on fly dispersal. We include the impact of this meteorological factor in our model by introducing a seasonal factor to the number of flies released per unit of time Π. The factor is calibrated from the monthly data for *Bactrocera (Bactrocera) tryoni* in Queensland from the 1950s (Atlas of Living Australia (2015)) as a proxy for PFF.

1.2.6 Economic model

The economic cost of a PFF outbreak can be classified into four broad categories: surveillance costs, production losses, eradication costs, and trade and revenue loses due to the loss of market share. Following Florec et al. (2010), let surveillance cost depend on labour costs for checking the traps and for trap maintenance. While trap maintenance cost can be fixed as cost per trap each year (g), labour costs have to be calculated based on per trap visits and duration, and this depends on trap density or grid size. The number of traps inspected can be calculated as:

$$X = \frac{h}{\left(\frac{\alpha}{v}\right) + \beta} \tag{3}$$

where X is the number of traps each inspector can visit in a given period of time, h is the weekly working hours per each inspector, α is the distance between traps, v is the travel time between traps, and β is the time spent on checking each trap.

We assume the number of trap visits $Q(d)$ to be a function of between trap distance d (or grid size). The total surveillance cost for a weekly surveillance regime can then be calculated as the total of labour costs, equipment cost (i.e., vehicles) and trap maintenance costs:

$$C^S(d) = \frac{Q(d)}{X}(w_I + E + s(w_S + M)) + Q(d)g \tag{4}$$

where w_I and w_S are the annual salary for trap inspectors and their supervisors, s is the ratio of supervisor to inspectors, E is annual equipment cost, and g is the annual cost of running a trap.

Production losses and eradication costs depend on the detection of PFF in a host cell. Here we ignore the production losses before a PFF detection. If the flies are undetectable then their damages are not (yet) significant. Infected or not, an eradication campaign will be carried out around the trap with a positive detection. The number of positive detections D at t can be represented by the current infection status (Y_t) and grid density:

$$D_t(Y_t, d) = f(Y_t, d) \tag{5}$$

Combining Equations 2 and 5, the expected production and damage costs at any given week can be calculated (we drop Y_t and use Ξ_t as it can be understood that Y_t can be solved using Ξ and Y_0) as:

$$C^E(d) = \pi \mathbb{E} \sum_{\tau}^{\mathcal{T}} D_\tau(\Xi_\tau, d, p) \otimes (c^E + c^P) T^M \tag{6}$$

where π is the outbreak arrival rate (probability), D_τ is the set of all detections at time τ from the beginning of the outbreak (note that we use a different time notation here to reflect the point that the summation in Equation 6 is over outbreak duration), Ξ_{tau} is the set of all information (or equivalently the random events realisation) available at τ, c^E and c^P are eradication and production losses at detection points, $\mathcal{T}$ is outbreak duration, and T^M is the management period. Once a positive detection is confirmed, a 15km containment buffer zone will be set up around the cell and treatment and eradication will be applied within that 15km buffer zone. The values c^E and c^P will, therefore, include the cost for the whole 15km buffer zone, not only the detected cell alone. Note too the values c^E and c^P are localised, and that will be an advantage of our heterogeneous space approach.

The argument for Equation 6 is similar to the approach of (Epanchin-Niell et al., 2012) in that an outbreak can happen at any moment with probability π. Therefore, at every t, the probability that we can get an outbreak aged τ is π. The expected total damage cost is, therefore, the sum of all expected costs caused by outbreaks at all ages $\tau \in [0..\mathcal{T}]$.

Similarly, at every time t, with a probability π of a new outbreak, we have a π chance of getting a trade sanction and loss of market access. There are two components to a trade sanction: the duration of the management period $T^D(\Xi, d, p)$ (i.e., time between first and last detection) and an additional waiting period (here we assume the waiting period to be T^M for simplicity). The value T^D is a function of the available prior-information, the surveillance grid density and the natural detection point, so

$$C^T(\Xi, d, p) = \pi\mathbb{E}[T^D(\Xi, d, p) + T^M]R_d \tag{7}$$

where R_d is the daily trade revenue loss due to the loss of market share.

The problem is now well defined. We chose the surveillance grid density d to minimise total cost:

$$\min_d TC(d) = \min_d\{C^S(d) + \pi\mathbb{E}[\sum_{\tau}^{\mathcal{T}} D_\tau(\Xi_\tau, d, p) \otimes (c^E + c^P)T^M + (T^D(\Xi, d, p) + T^M)R_d]\} \tag{8}$$

or more compactly:

$$\min_d TC(d) = \min_d \mathbb{E}[F(\Xi, d)] \tag{9}$$

By design, the idea is to minimise all of the losses associated with a potential PFF incursion and spread and the cost of the surveillance program itself. The more dense is the trapping grid the more expensive is the surveillance activity, but detection is also earlier and potential damages smaller. The less dense is the trapping grid, the smaller are surveillance expenditures but potential damages from an incursion and spread are much larger.

1.2.7 Planning horizon

We choose week as the unit of time in our model, rather than a day. The advantage of a weekly modelling approach is to reduce model size, which involves a massive half-million horticultural raster cells as it is. Trap visit frequency is also assumed to be weekly, as is common in practice.

Another key point in determining the planning horizon is to define the end point, an important determinant of the exact cost of an outbreak. If our simulation ends with untreated infested cells, then the cells will pass flies on, and future costs are incurred. Therefore, we choose a fixed planning horizon (15 months) and apply a penalty rate for undetected cells. At the end of the planning horizon, in other words, we apply a penalty for all (as yet) undetected and infested hosts that could be infested with (still travelling) propagules. The size of the penalty rate is a subjective judgement. In our case, we assume that a 15km eradication buffer (following Dominiak, 2007) will be applied to all undetected hosts. Given the fact that the infested hosts are usually in close proximity, this seems sufficient. It's worth noting that an application of a buffer zone of this type to all infested hosts will generally increase outbreak management costs.

1.2.8 Sample Average Approximation Approach

We need a computational algorithm to solve an optimisation problem with such a large dimension. We use a sample average approximation approach (SAA), following Shapiro (2003). Consider the spatial dynamic stochastic programming problem given by Equation 9, where Ξ is a multiple-dimensional random variable. If Ξ is discrete random variable and we have a finite number $\mathcal{N}$ of possible realisations our problem can be written simply as:

$$\min_d \{TC(d) := \frac{1}{\mathcal{N}} \sum_i^{\mathcal{N}} \eta_i F(\xi_i, d)\} \tag{10}$$

where η_i is the probability of ξ_i realisations of Ξ. However, in our case, the number of realisations is extremely large, so we can only generate some sample (N) of it and approximate our minimisation problem by:

$$\min_d \{\hat{TC}(d) := \frac{1}{N} \sum_i^{N} F(\xi_i, d)\} \tag{11}$$

It is well known that $\hat{TC}(d)$ is a consistent estimator of $TC(d)$. The proof of the statistical properties of SAA and its rate of convergence can be found in Shapiro (2003). That said, for validation, we need to estimate the upper and lower bounds of the optimal value function $v^* = \min_d TC(d)$. Denote $\hat{v_N} = \min_d\{\hat{TC}(d)\}$ then, following Shapiro (2003), the lower bound of v^* can be estimated by the average of $\hat{v}$ over M independent samples with each N realisations of Ξ:

$$\underline{v}_{M,N} = \frac{1}{M} \sum_i^{M} \hat{v}_N^i \tag{12}$$

The variance of $\underline{v}_{M,N}$ can be estimated by:

$$\hat{\sigma}^2_{M,N} = \frac{1}{M}\left[\frac{1}{M-1}\sum_i^{M}(\hat{v}_N^i - \underline{v}_{M,N})^2\right] \tag{13}$$

The upper bound of v^* can be estimated with any optimal decision candidate $\hat{d}_m$ $(m \in M)$ by generating another sample with N' realisation of Ξ and calculating $\overline{v}_{N'}(\hat{d}_m) = \hat{TC}(\hat{d}_m)$. The variance of the upper bound can be estimated by:

$$\hat{\sigma}^2_{N'}(\hat{d}_m) = \frac{1}{N'(N'-1)} \sum_i^{N'} \left[F(\Xi_i, \hat{d}_m) - \overline{v}_{N'}\right]^2 \tag{14}$$

The upper bound can be calculated for every solution candidate from the above M samples. However, we are only interested in the best candidate. For unbiased selection, following Verweij et al. (2003) and Sheldon et al. (2010), we generate another sample with N'' realisation of Ξ. The best candidate $\overline{d}$ is the one among $\hat{d}_m$ with the lowest $\hat{TC}(\hat{d}_m)$. The optimal gap can be calculated as $\overline{v}_{N'}(\overline{d}) - \underline{v}_{M,N}$. The SAA problem is thus, when put this way, an iterative process and we can continue to increase M, N, N', N'' until the gap and (the above) variances are small enough.

1.2.9 Numerical Algorithm and Results

In the section, we provide the results of our numerical analysis. We will first discuss the sampling method, implementation of a parallel processing routine, and parameterisation. The model validation and numerical results will follow. Numerical results and plots are obtained using C, and R R Core Team (2014). For R in particular we use the following packages: maptools 0.8-36 Bivand and Lewin-Koh (2015), raster 2.3-40 Hijmans (2015), rasterVis 0.31 Perpinan and

Hijmans (2014), rgdal 0.9-2 Bivand et al. (2015), sp 1.1.0 Pebesma and Bivand (2005); Bivand et al. (2013), plotrix 3.5.11 Lemon (2006), and ggplot2 1.0.1 Wickham (2009).

1.2.10 Exterior sampling

Optimisation is (very often) just a basic iterative process, in which we move in a direction where the objective function is improving over time. In order to ensure an improvement in the objective function we need to compare values. For deterministic optimisation, the comparison is trivial. With SAA, this is not the case. In SAA, we compare samples and then compare errors, as usual, but the key when comparing errors under uncertainty is 'efficiency'. There are two ways to improve efficiency in SAA optimization: one is to increase the number of samples and the other is to use an exterior sampling approach. The exterior approach is different from its interior sampling counterpart in the sense that with exterior sampling all random events are realised before a policy application (i.e., the use if traps in our case). The benefit of exterior sampling can be clearly seen when we have only a single observation: when all random events are realised the problem becomes deterministic and all comparisons of the objective function (with different policies) are deterministic and exact. With a multiple sample SAA problem, we can not ensure an exact comparison but, according to Shapiro (2003), as the objective function is an average of individual samples, where policies are applied under the same scenario, the objective function values tend to be positively correlated, and the error comparisons tend to be smaller.

In our paper, we apply an exterior sampling approach by generating all possible infestations and fly dispersals from an initial single cell infection at time $t = 0$. An infested cell will remain so forever (within our planning horizon). With multiple infestations, where a cell can be visited by different propagules at different times, it's clear that one of the infections will be successful, and it need not to be the first propagule. Similarly, we also do not stop the simulation of a travelling propagule once it reaches a host. It can trigger an infestation, but we do not know if it is the first propagule reaching the cell in a single simulation, and thus it may continue moving.

With our exterior sampling approach, it is clear that all possible infestations and propagule movements are generated before any policy application or, again, in our case, before the surveillance grid is put in place. In the last SAA optimisation step, we apply a surveillance grid to the raster map. Every propagule within some sensitive distance around the traps will be attracted to it and will be killed. The attraction also triggers a positive finding and a 15km eradication zone, where infested hosts and propagules will be treated and terminated. Working forward, we can find all infestations and eradicate in every outbreak.

The downside of the exterior approach is the size of the simulation. As the hosts remain infested for the entire planning horizon, they keep producing flies and flies keep infesting new hosts. To that extent, we can apply two limited trimming rules to help reduce simulation run size: (a) we can terminate the first host after it has been naturally detected, and (b) we can terminate a particular propagule's journey if it first reaches a clean host.

1.2.11 Parallel processing

The advantage of our approach is that we can model fruit fly behaviour and spread in a high resolution map (much like Figure 3). But, of course, high resolution modelling comes with a high computational cost. With the size of a raster cell as small as 50 by 50m, the horticulture area in Queensland alone consists of more than a half-million cells and flies can colonise in any of those cells. As the cells size are small, our medium uncontrolled outbreak potentially involves more than 1500 cells. Each one of those cells continuously releases flies (maximum 4 propagules each week), and each propagule lives for ten weeks and travels to a number of cells. All of this information needs to be 'stored' throughout the computational analysis, and the storage and computation requirements grow very quickly with the number of simulations. As an example, with our standard 2400 simulation runs (per process, see Table **??** bellow), the number of flies landing in cells is more than a half-billion, which is sizeable for any personal computer.

To tackle that computational challenge, we use a parallel processing algorithm. employing several computers and processes at the same time. The advantage of parallel computing is not only to increase the number of simulations, but also to separate the optimisation process into smaller pieces, which can be handled in parallel. By doing so, we do not need to feed all of accumulated simulation results into the memory of a single computer, so that the size of the simulation simply depends in the number of computers in use.

1.2.12 Scenario design

PFF migration from PNG via the Torres Strait islands is by far the most likely PFF threat for Queensland. The Torres Strait Fruit Fly Strategy has been designed to prevent permanent establishment of exotic fruit flies in the Torres Strait to reduce the risk of them moving south to mainland Australia, via Queensland (**?**). Given that prior, we limit the PFF incursion in Queensland to an area of about 1000 raster cells in the far north of Queensland (above 16.5^{o}S latitude). A PFF outbreak begins when flies settle in a random cell within the incursion area. Once settled, PFF will gradually expand in a southerly direction.

1.2.13 Parameterisation

Table 3 represents all of the parameter values that we use in our model. There are several parameter values worth highlighting. The first is the trap sensitivity buffer zone. In our work, we assume it to be 500m circle around a trap. We adopt this number following Adeva et al. (2012), who indicates that flies can detect a host with near certainty if they are within 100m from the host or trap, and with at least 70% certainty for cases 500m from the host. Bait are used in traps, so a fly can sense the trap in the same way as it senses a natural host.

Second, in terms of the probability of long distance dispersal, we adopt the value 0.3 from Adeva et al. (2012). However, unlike Adeva et al. (2012), we use only two discrete dispersal regimes, one long and one short dispersal. Although, we randomly choose actual travelling distance within each regime, we assume that each propagule can choose only one of the regimes at a time, especially in the first week of its journey. Further, a jump generally occurs only in the first week when a fly is stronger and more active.

Third, the estimation of the direct economic cost of having a PFF outbreak varies considerably. Cantrell et al. (2002) estimate the cost of a four year PFF outbreak in Queensland to be $100 million, while (Hafi et al., 2013) estimate fruit flies (of all sorts) could cost Australia roughly 3.3 billion AUD (over a hundred year horizon). We proxy our revenue losses by the Cantrell et al. (2002) estimate since it is drawn from the part of QLD closest to our scenario design.

Finally, not only are direct economic losses important, the length of market closure also matters. Underwood (2007) studies the costs and benefit of a fruit fly outbreak in New Zealand and finds market closures can last from 8.5 to 11.5 months. We follow Underwood (2007) and assume an 8.5 month trade restriction for Australia. For simplicity, we also assume that limits to domestic production are also 8.5 months, during which horticultural production in restricted areas generates losses of about 45% of its total value (Kompas and Che, 2009).

Table 3: Model parameterisation

Coefficient	Description	Unit	Value
	Surveillance parameters		
	Natural detection	month	6
	Trap sensitivity buffer zone	km	0.5
	Treatment buffer zone from detection point[a]	km	1.5
	Production restriction buffer zone from detection point[a]	km	15
	Production restriction[b]	month	8.5
	Biological parameters		
	Incursion probability[f]		0.2
Π	Maximum number of departing propagule per week		2
	Early development period[kg]	week	4
	Adults survival period[kg]	week	10
	Long distance dispersal[c]	km/week	94
	Short distance dispersal[d]	km/week	1.4
	Probability of long distance dispersal[c,g]		0.3
	Economic parameters		
h	Number of working hours per week[e]	hour	37
v	Speed of travelling between traps	km/h	40
β	Time spent at each trap	minute	4.14
g	Cost of trap maintenance[e]	\$/year	9.75
	Annual vehicle cost[e]	\$/car	15,000
	Rate of supervisor/inspectors[e]		1/3
	Annual inspector's salary[e]	\$	66,700
	Annual supervisor's salary[e]	\$	82,200
	Inflation factor[e]		1.029
	Percentage of production revenue damages in infected cells[f,g]	%	45
	Control cost per km^2[f]	\$	539
	Annual revenue loss[h,g]	\$ mil	25
	Queensland's horticulture gross production revenue		
	Fruit[i]	\$ mil	864.77
	Vegetables and herbs[i]	\$ mil	376.66
	Citrus[i]	\$ mil	83.18
	Grapes[i]	\$ mil	55.67

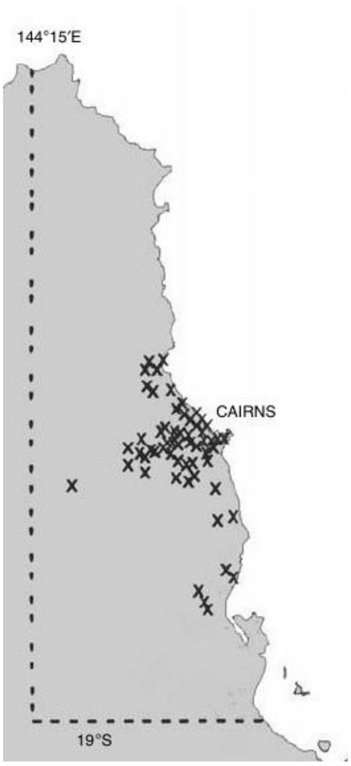
Notes: [a]Dominiak (2007), [b]Underwood (2007), [c]Dominiak (2012), [d]Adeva et al. (2012), [e]Florec et al. (2010), [f]Kompas and Che (2009), [g]Authors approximation, [h]Cantrell et al. (2002), [i]ABS (2015), [k]Bateman (1967)

1.2.14 Model Calibration

Model calibration is needed before the SAA approach can be implemented. In our model, the maximum number of propagules released weekly (Π) is a key factor behind the transmission of PFF in the local neighbourhood. To calibrate, we adjust this parameter to replicate the outbreak of PFF in north Queensland in 1995. It is widely believed that the flies were present 12-15 months before detection in October of that year. In our simulation, we let PFF disperse freely (undetected) for 16 months from September 1994 and compare our simulation results with the actual positive PFF detection in November 1995. Figure 6b plots infected raster cells in a medium size outbreak among our 100 simulation runs. With $\Pi = 2$, our model can replicate the observed or actual positive PFF detection in Figure 6a well. Note that Figure 6b only depicts infected hosts, not travelling flies. With travelling flies we expect a larger outbreak coverage, and hence our simulation will look even more like the actual positive detection.

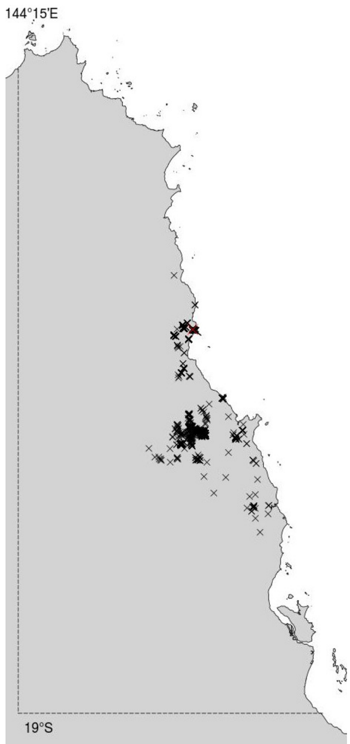
Figure 6: PFF outbreak in north Queensland in November 1995: actual vs simulation results.

(a) Observed PFF positive trap.



Source: Fay, et al. 1997.

(b) Simulation results.



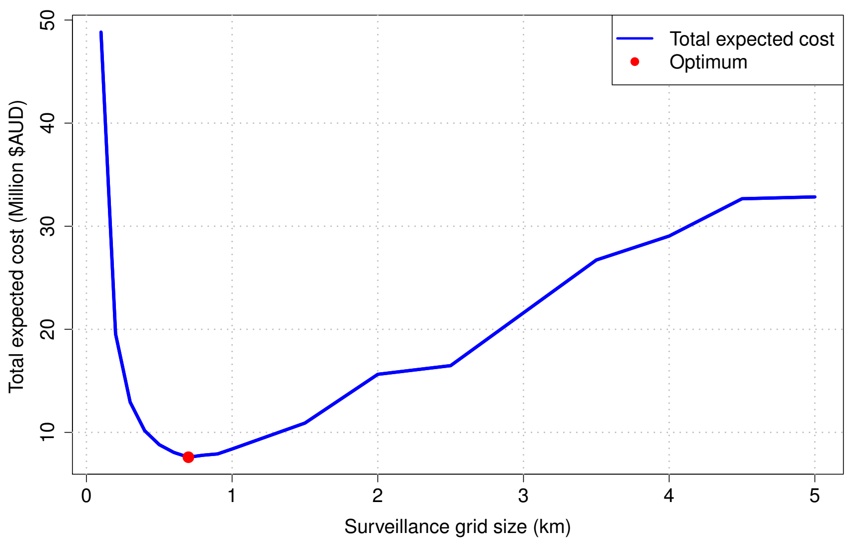
Source: Author's calculation.

1.2.15 Results

It is clear that early detection can reduce outbreak size, economic losses and the cost of management. However, to reduce detection time, we would need to design a denser surveillance grid and that will increase surveillance cost. If we apply a 10% rule (we place a trap in every grid cell with horticulture taking more than 10% of its area) then the number of traps for Queensland increases from 137 with a 5km grid size to 221 with 4km, 982 with 2km, 3569 with 1km, 5342 with 0.8 km, 6782 with 0.7 km and nearly 170 thousand with a 100m grid size. With this exponential increase in the number of traps as grid size falls, we would naturally expect a trade-off between the benefit of early detection, in terms of all avoided losses, and the cost of surveillance as a result of the number of traps used to detect early.

Equations (9) and (11) can exploit this tradeoff and find an optimal value for surveillance grid size. Solving the model, we plot in Figure 7 the total expected cost of all economic losses and the cost of the surveillance program itself, across different sizes of the surveillance grid, approximated by 360 simulation runs. Figure 7 indeed confirms the trade-off between damage costs and surveillance costs: as grid size decreases, the cost of the surveillance program itself increases total costs; as grid size decreases the otherwise avoided losses, from not having a point of earlier detection, now increase total costs.

Figure 7: Total expected outbreak cost of PFF surveillance.



Further simulations of the SAA approach, we fix M, N', N'' and increase N to check for the 'optimality gap'. With $N'' = 33,600$ runs, the upper bound of the optimal total expected cost stabilises at \$7.58-\$7.59 million. The lower bound is also clearly approaching the upper bound when N increases. The optimality gap is quite small as $N > 288$ and not significantly different from zero. This suggest that our overall 100,800 simulation runs are adequate to provide credible results for our optimization problem. The precise optimum grid size is, therefore, around 0.7 km. This is significantly denser than the current 5 km surveillance grid for Queensland as indicated in Kompas and Che (2009).

1.3 Model 2: Basic aggregative model

In this section of the report, we use a basic and more aggregated spatial bioeconomic approach applied directly to measure the potential cost of PFF in QLD. Optimality is set aside, we instead focus on providing basic measures of total economic damages. There are three key assumptions. First, the local value of horticulture used in this report is the 'Local Value' (direct farm value) rather than Gross Value of Production. It is thus assumed that the cost of a pest would only occur mainly at the farm level (directly affecting fruits or vegetables). Due to lack of available parameters some indirect farm costs in the value chain (such as transportation and retail sectors, etc.) are not estimated. Second, it is assumed that the highest risk area in terms of a PFF outbreak is in Queensland, given its proximity to the Torres Strait and its local conditions which are suitable for a PFF establishment and spread. Third, only horticultural industries subjected to PFF are included in this analysis.

1.3.1 Risk assessment

At present Australia is PFF free country after the successful 1995 eradication of outbreak near Cairns. However, the risk of a PFF outbreak is likely to be increasing given the increased movements of people and goods through the Torres Strait and the recent and often widespread outbreaks of PFF in South-East Asia and Papua New Guinea since 1992. In this study, we focus on Queensland, in particular, and use existing information provided by Plant Health Committee (2013). We assume that the probability of a PFF incursion and spread is given by a basic 'triangular distribution', (i.e., minimum, most likely and maximum values), with a 1:25 year chance of an incursion on the mainland of Australia, and a 10 per cent range on minimum and maximum values. Additional expert elicitation may further refine these parameter values and the properties of the distribution.

1.3.2 Modelling of PFF potential costs

Our spatial and temporal modelling generally follows Lopes et al. (2008) and our simulations are guided by material in Vose (2000). The population (measured as infested farms) of PFF will grow from location to location, and through time. At time at $t+1$, the infested farm (N) of PFF at location s is given by

$$N(t+1, s(\vec{x}_{t+1}, \vec{y}_{t+1})) = F[p_{ij}, \mu(t)^{N^*}, \beta(s(\vec{x}_{t+1}, \vec{y}_{t+1})), f(t), \xi] \tag{15}$$

where the PFF infested population $N(t{+}1)$ is two-dimensional vector of locations $s(x, y)$ (*where*) and time (t=1-T) (*when*); $f(t)$ and $\beta(s(\vec{x}_t, \vec{y}_t))$ characterises movement over time and space; $\mu(t)^{N^*}$ is a simulated dynamic over time and space; and ξ represents uncertainty.

The population of infested farms at time $(t+1)$ and space j follows an assumed logistic function given by

$$N_{t+1,j} = N_{1,j} + r_j \left[1 - \frac{N_{tj}}{Nmax}\right] - m_{tj}N_{tj} \tag{16}$$

where the spatial domain (s) is subdivided into a set of discrete patches j to Ω; r is the growth rate of PFF; $m_{tj}N_{tj}$ is infested areas reduced by management m_tj; and $Nmax$ is maximum carrying capacity.

The spatial economic impact caused by the spread of PFF depends on time, spread and relevant economic parameters. The economic parameters of the potential costs caused by PFF can also vary by time and space. If PFF become endemic, the pest would have multiple effects on the horticultural industry, including

$$C_{t+1,j} = \overbrace{N_{t+1,j}c(m)_j}^{Management\,cost} + \overbrace{N_{t+1,j}y_{t+1,j}M_j(p_j - p_{2j)}}^{Market\,access\,loss} \tag{17}$$

where $c(m)_j$ is the PFF management cost for commodity j; y is the yield of variety j at time $t+1$; p_j is the price of commodity j; p_{2j} is the market loss caused by restriction of fruits to other markets; and M is the market share of commodity j in total production.

In this report, we simply combine a spatial mapping (GIS) tool with an assumed logistic growth model, given parameters for spread, prices and costs of PFF. Parameter values are as indicated below. To visualise, we map infested farms, using MapInfo, month-by-month, randomly simulated based on the number of farms located in an area, given an assumed initial outbreak in the Wet Tropic region.

1.4 Estimation of PFF potential costs in Queensland

1.4.1 Key assumptions and data sources

There are a number of key assumptions for estimating the potential cost of PFF used in this study. Along with the Local Value of production mentioned earlier, we assume:

- Risk zones of PFF are horticultural farms, which are potential hosts for PFF;
- PFF spread is generally assumed from north to south;
- Given the current preventive measures and frequency of PFF surveillance, the most likely probability for the next incursion is 1:25 years. Future values and production values of the host industries are assumed to be based on the current situation.
- A PFF outbreak would cause market access losses. In particular, the loss in market access results in lower prices for fresh fruit sold domestically compared to premium (export) markets along with lower prices overseas.
- Parameter values for spread and economic damages are drawn from Monzu et al. (2002), Kompas and Che (2003) and Kompas et al. (2015). In particular, it is assumed that from an initial establishment it takes four weeks to produce a new generation, so that after four weeks PFF develops, say, from the initial area of (1.5 km2 to an infested area of 2.25 km2 (the first generation). The maximum area for Wet Tropics is 8,844 km2 and spread rates are assumed to vary for 0.475 to 0.563 per month, with a mean value of 0.538.
- The database of farm production and the gross value of farm gate values by commodities for Queensland, by region, is provided from the ABS (2014a,b), DAF of Queensland (2015), Horticulture Australia (2014) and Business and Industry of Queensland (2015). The Consumption Price Index (CPI) is based on ABS (2015). The protocols for PFF containment are based on Bugforbug (2015), the Florida State Horticultural Society (2015) and DAF of Queensland (2015). Containment costs of PFF depends on the number of spray regimes (per hectare or per tree) of different commodities and are as detailed in Pimentel (2002), the Florida State Horticultural Society (2015), and Bugsforbugs (2015).
- All values are at 2015 prices, and the discount rate used for estimating net present value is 0.03/year.

1.4.2 Potential cost of PFF in horticultural regions

This section provides the key results of the potential cost of PFF in QLD to the major horticultural areas and the region as a whole. The potential cost of PFF is estimated by the nominal cost per year and the total net present values of the potential total costs of PFF over a lifetime of eradication (25 years). Potential costs form PFF at farm level are classified by high, medium and low costs given by large, medium and small farm sizes. Based on Figure 2, the farm gate value is taken as $1 million, from $400–$650,000 and less than $170,000 for large, medium and small farms. Given the distribution of farm gate values in QLD, the potential cost of PFF varies by farm size and commodity, which is calibrated by very high, high, medium and low corresponding to an average farm gate value of more than \$3 million, around \$1 million, between \$400,000-\$600,000 and less than \$400,000, respectively.

Wet Tropic region

Table 4 provides the key facts of the PFF host farms/industries in this region. In 2013, the total GVP of these industries was \$507 million. The most important commodities are bananas, avocados and mangoes. Bananas are the largest fresh horticulture crop available year-round, selling more than any other fruit on the market in Australia. The Wet Tropic region in Queensland produced about 93 per cent of Australia's bananas in 2012-13. There are approximately 200 banana farms (Queensland Government 2015 and ABS 2014a,b). In the Wet Tropic region, bananas are the most important commodity, accounting for more than 90 per cent of the total farm gate value of horticulture (see Table 4). In 2013, the production of bananas was about 300,000 tons with a \$396 million farm gate value. Avocado, mangoes and strawberries are the next most important commodities, contributing \$34.5, \$13.4 and \$5.2 million of farm gate values in 2013, respectively. The simulated distribution of farms and average farm gate value per farm by major commodities are indicated in Figure 8. Figures 9 and 10 represent the cost of PFF spread in the Wet Tropic region at year 1 and year 2, classified by three different levels of farm costs (low, medium and high).

Table 4: Production and value of PFF host industries in the Wet Tropic region, 2012–13

Commodity	Production *(tons)*	GVP *(\$mill)*	Local value *(\$mill)*
Bananas	299,602.2	443.99	396.05
Avocados	10835.0	40.96	34.50
Mangoes	7536.1	15.93	13.43
Strawberries	1186.5	6.07	5.16
Capsicums	164.5	0.43	0.36
Nectarines	8.6	0.02	0.01
Peaches	8.6	0.01	0.01
Tomatoes	6.4	0.01	0.01
Total	319,548.0	507.42	449.53

Source: Australian Bureau Statistics, 2014a,b.

Table 5 presents the estimated results for the potential cost of a PFF incursion in the Wet Tropic region. The nominal cost per year is about \$6.7 million. Over 25 years, the total net present value of a PFF is about \$106 million, of which the cost to the banana industry is most important accounting for 83 per cent of the total loss.

Figure 8: Simulation of farm distribution and farm gate value for the Wet Tropic region (*$'000 & farm number)*

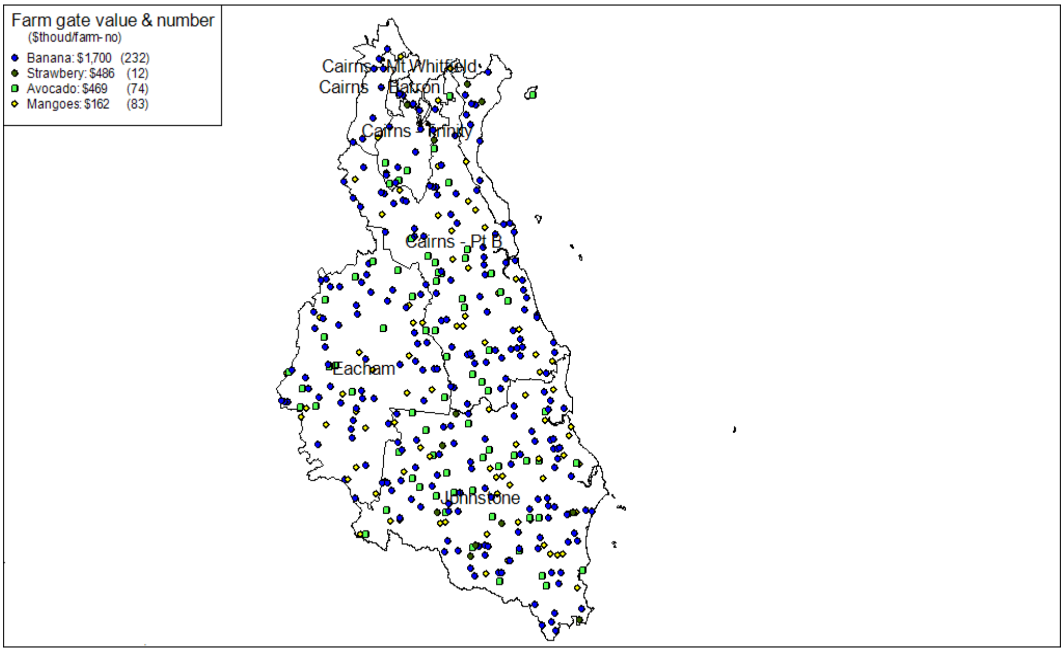


Figure 9: Simulation of the cost of PFF spread in the Wet Tropic region: Year 1

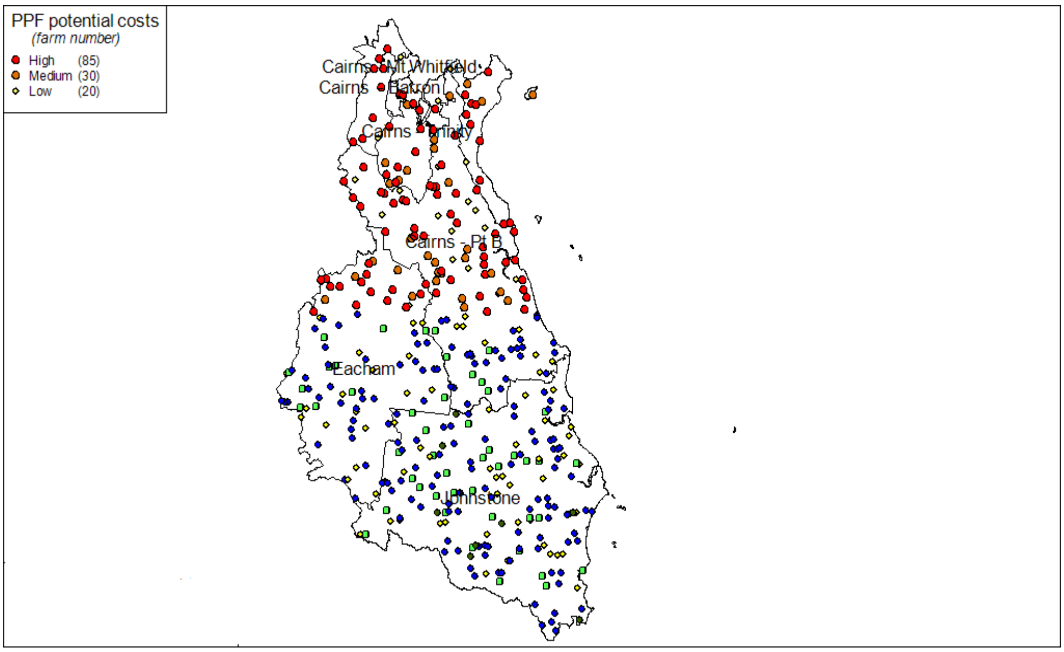


Figure 10: Simulation of the cost of PFF spread in the Wet Tropic region: Year 2

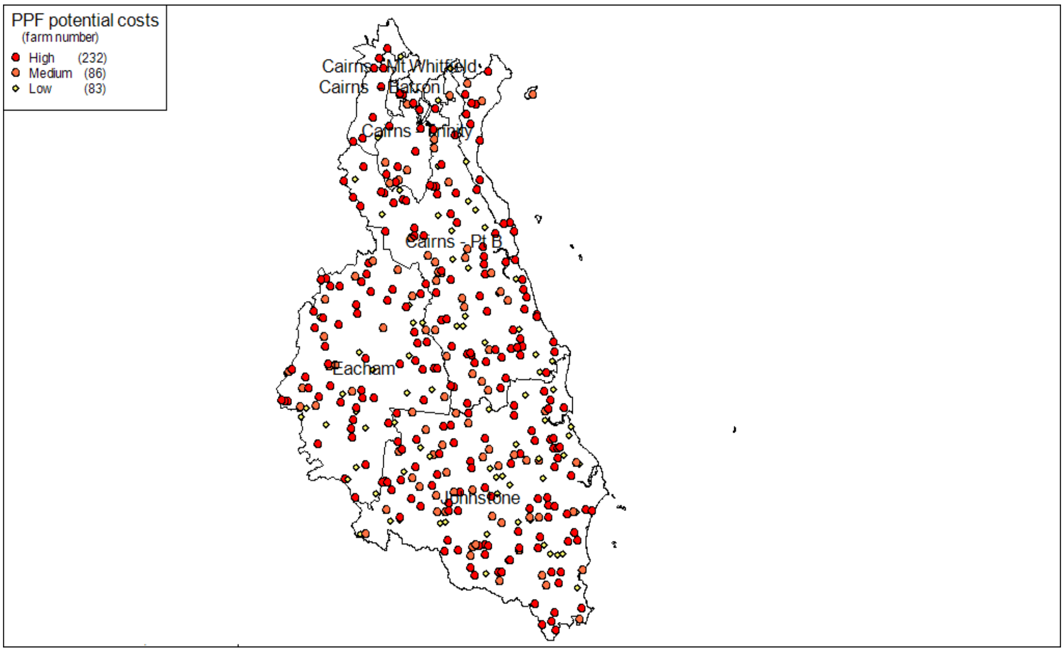


Table 5: Potential cost of PFF endemic in the Wet Tropic region ($)
(*most likely value*)

Commodity	PFF cost	Market accesses loss	Net Present Value of benefit of eradication
Banana	$5,611,100		$88,049,600
Avocados	$543,700	$88,100	$9,914,100
Mangoes	$376,500	$106,300	$7,576,800
Strawberries	$22,500		$353,200
Others	$6,100		$95,300
Total	$6,559,900	$194,400	105,989,100

Burdekin region

Table 6 provides key facts for PFF host industries in the Burdekin region. In 2013, the total GVP of PFF host horticultural industries in the region was about $130 million, of which tomatoes, capsicums and mangoes contributed for $87.7, $20.3 and $15,4 million, respectively.

Farm size measured in terms of farm gate value varies significantly for tomatoes, bananas, capsicums, grapes and strawberries and mangoes as indicated in Figure 11.

Table 6: Production and value of PFF host industries in the Burdekin region, 2012–13

Commodity	Production *(tons)*	GVP *($mill)*	Local value *($mill)*
Tomatoes	51,848.0	1 05.39	87.7
Capsicums	9,288.0	24.33	20.3
Mangoes	8,621.5	18.23	15.4
Bananas	5.0	7.40	6.6
Grapes	0.54	0.5	
Total	60,474.5	155.89	130.39

Source: Australian Bureau Statistics, 2014a,b.

The potential cost of PFF endemic in the Burdekin region classified by high, medium and low costs for different farm sizes is presented in Figure 12. Given the very large farm sizes of the 14 tomatoes farms, with farm gate values of more than $6 million, the potential cost of PFF for these farms would be considerable. Table 7 provides the summary results of the potential costs of PFF in terms of the average nominal cost per year and the total net present value over 25 years by major commodities.

Table 7: Potential cost of PFF endemic in the Burdekin region ($)
(*most likely value*)

Commodity	PFF cost	Net Present Value: Benefit of eradication
Tomatoes	$467,100	$7,119,000
Mangoes	$180,000	$2,742,900
Capsicums	$522,200	$7,959,600
Others	$141,700	$2,159,900
Total	$1,311,000	$19,981,500

Figure 11: Simulation of farm distribution and farm gate value for the Burdekin region (*$'000 & farm number)*

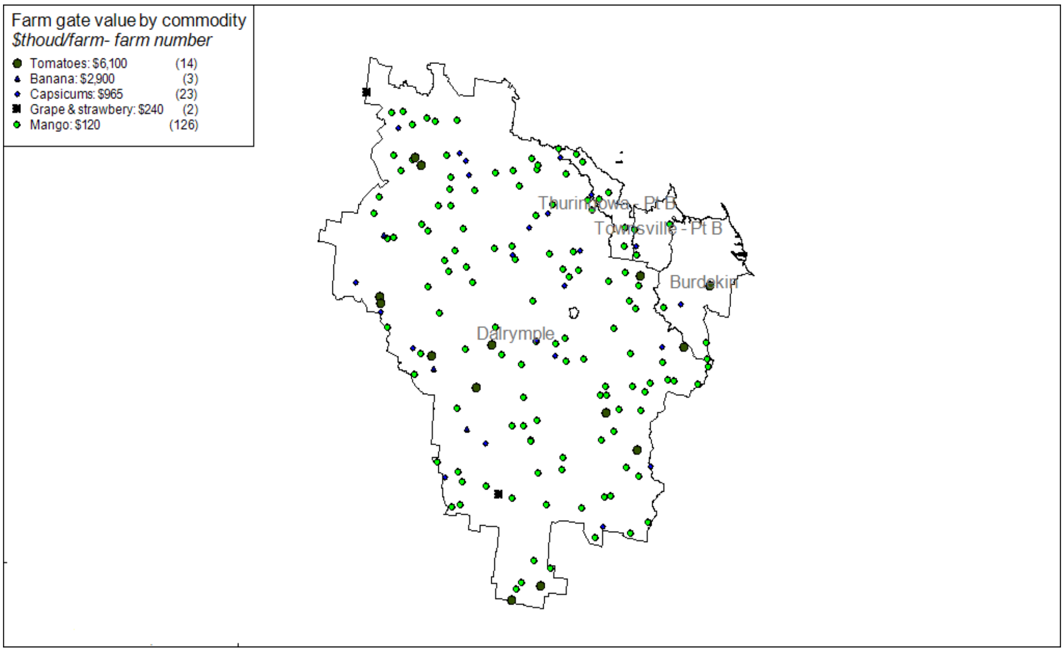
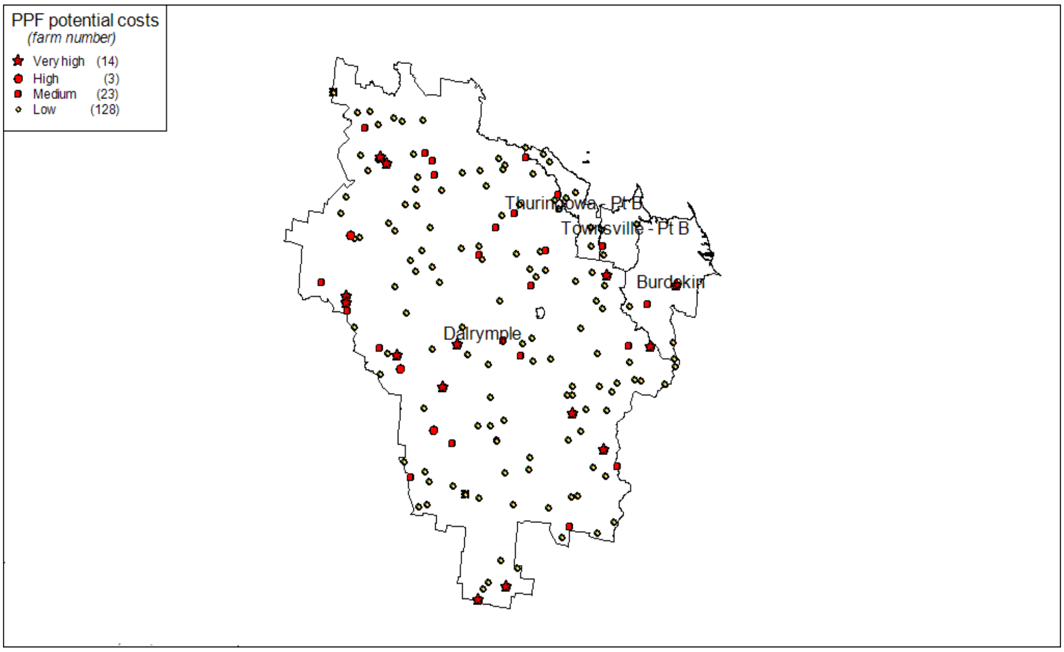


Figure 12: Simulation of the cost of a PFF endemic in the Burdekin region



Burnett Mary region

Queensland grows about 2500 hectares of citrus (ABS 2014b). The main production areas are Mundubbera and Gayndah in the Central Burnett and Emerald. Minor production areas include Bundaberg, Howard, Mareeba, Maryborough and the Sunshine Coast.

Mandarins, mainly Imperials and Murcotts, are the main citrus fruit grown in Queensland with smaller areas for oranges, lemons, limes and grapefruit. Most fruit is grown for the fresh fruit market, but a percentage of the orange crop is used for juice production. Citrus fruits are grown in orchards from grafted or budded nursery stock. Fruit is harvested from January to October with the bulk of the crop picked between March and July. Most of the fresh fruit produced is marketed in the major metropolitan wholesale markets of Brisbane, Sydney and Melbourne, but a large and increasing amount of the mandarin and orange crop is being exported (see Business and Industry of Queensland).

Table 8 provides data for PFF host industries in the Burnett Mary region. In 2013, the total GVP of these industries was $250 million. The most important commodities are tomatoes, mandarin and avocado. Average farm gate value by commodity is presented in Figure 13 showing that farm gate values of tomatoes and capsicum farms are the largest in the region.

Table 8: Production and value of PFF host industries in the Burnett Mary region, 2012–13

Commodity	Production *(tons)*	GVP *($mill)*	Local value *($mill)*
Tomatoes	44,430.1	90.31	75.12
Mandarins	54,340.2	76.63	63.42
Avocados	15,417.8	58.28	49.09
Capsicums	6,078.8	15.92	13.27
Grapes	825.1	2.65	2.4
Bananas	1,613.3	2.39	2.13
Mangoes	939.9	1.99	1.68
Oranges	3,483.8	1.82	1.51
Strawberries		0.84	0.71
Nectarines	111.4	0.23	0.18
Peaches	94.7	0.16	0.13
Total	127,335.0	251.22	209.64

Source: Australian Bureau Statistics, 2014a,b.

The potential cost of a PFF incursion in the Burnett Mary region based on high, medium and low categories, is presented in Figure 14. Since roughly 30 per cent of mandarin production is exported and the major markets are PFF free, the potential loss of market access of mandarin could be as much as $1.9 million per year. On average the total nominal cost of PFF is about $4.3 million per year in this region. Total net present value of PFF over 25 years is estimated to be up to $54.7 million (see Table 9).

Figure 13: Simulation of farm distribution and farm gate value of the Burnett Mary region *($'000 & farm number)*

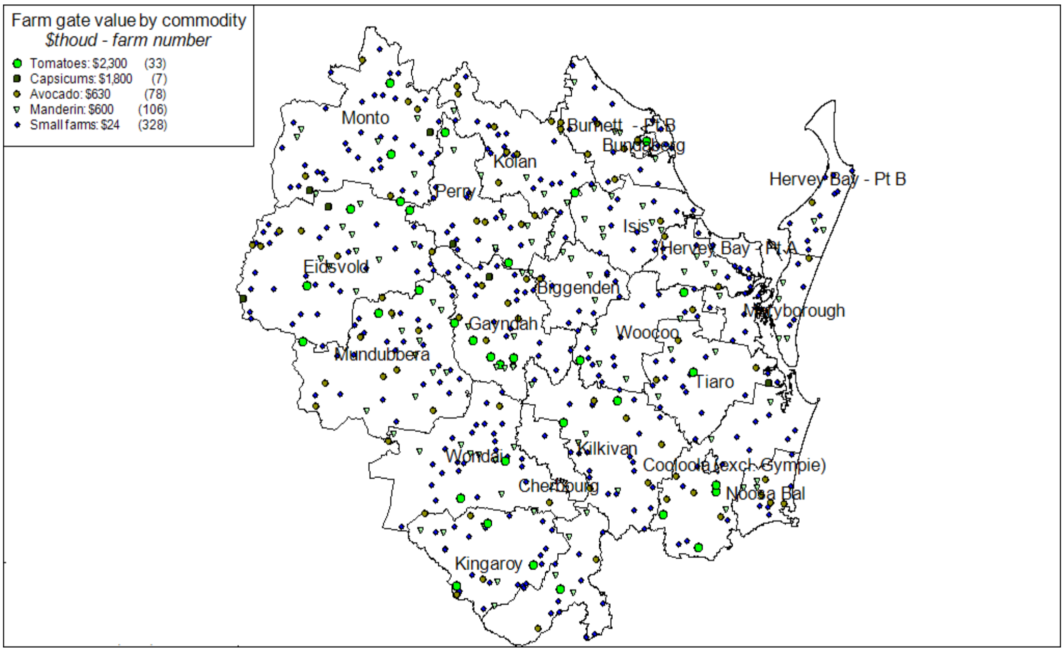


Figure 14: Simulation of the cost of an PFF endemic in the Burnett Mary region

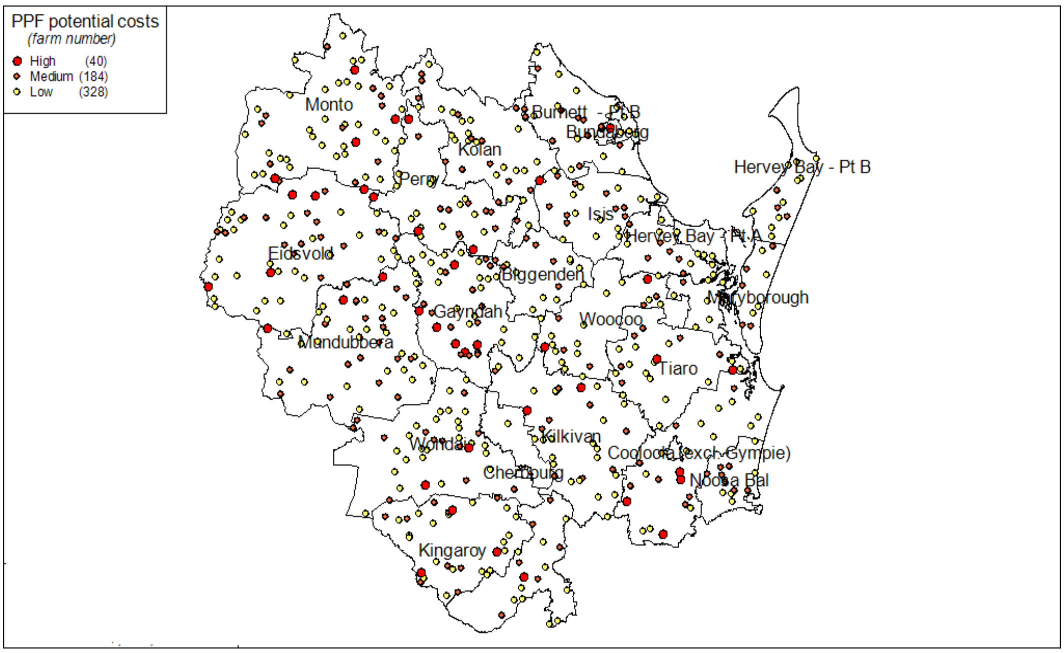


Table 9: The potential cost of an PFF endemic in the Burnett Mary region ($) (*most likely value*)

Commodity	PFF cost	Market accesses losses	Net Present Value: Benefit of eradication
Tomatoes	$238,900		$3,033,300
Mandarins	$655,100	$1,902,600	$32,472,900
Avocados	$846,100	$392,700	$15,728,800
Capsicums	$139,900		$1,776,400
Others	$78,600	$61,500	$1,778,800
Total	$1,958,700	$2,356,800	$54,790,200

Border Rivers Naranoa–Balonne region

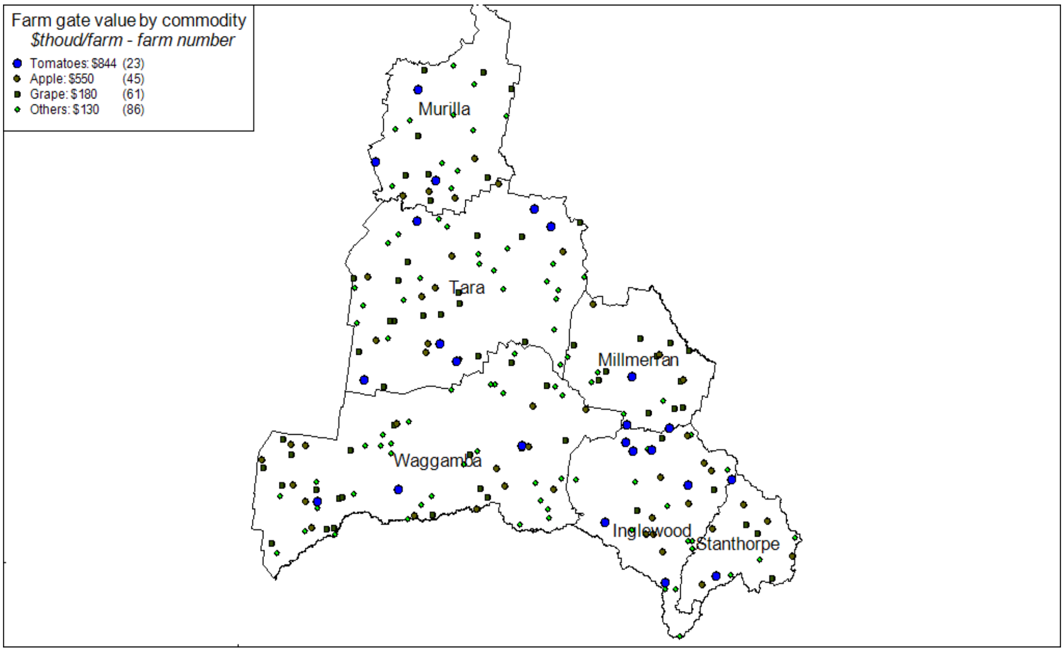
Table 10 provides the key data for PFF host industries in the Border Rivers Naranoa-Balonne region. In 2013, the total GVP of potential PFF host horticultural farms in the region was about $88.5 million, of which apple, tomatoes, grape, capsicums and strawberries are the most important commodities. Farm size measured in terms of farm gate value varied significantly across tomatoes, apples, grapes and other farms in the region (see Figure 15). Farm gate value is roughly $844,000 and $550,000 for tomato and apple farms, $180,000 for grape farms and less than $130,000 for other farms in the region.

Table 10: Production and value of PFF host industries in the Border Rivers Naranoa -Balonne region, 2012–13

Commodity	Production (*tons*)	GVP (*$mill*)	Local value (*$mill*)
Apples	34,002.2	45.21	37.63
Tomatoes	7,863.4	15.98	13.30
Grapes	3,879.6	9.01	8.08
Capsicums		7.38	6.15
Strawberries	948.7	4.85	4.13
Nectarines	1,140.4	2.34	1.88
Peaches	1,036.4	1.76	1.39
Mandarins	875.0	1.23	1.02
Pears (including Nashi)	343.6	0.55	0.49
Cherries	17.1	0.14	0.13
Total	50,106.4	88.45	74.20

Source: Australian Bureau Statistics, 2014a,b.

Figure 15: Simulation of farm distribution and farm gate value of the Border Rivers Naranoa-Balonne region (*$'000 & farm number)*



The potential cost of a PFF endemic in the Border Rivers Naranoa-Balonne region, calibrated by high, medium and low cost categories for different farm sizes is presented in Figure 16. Since a part of the overall grape production is exported to major markets that are PFF free, the potential loss of market access for grapes could be more than $100 thousand per year. On average, the total nominal cost of PFF is about $2.1 million per year. The total net present value of PFF over 25 years is estimated to be up to $27.5 million (Table 11).

Figure 16: Simulation of costs of PFF endemic in the Border Rivers Naranoa-Balonne region

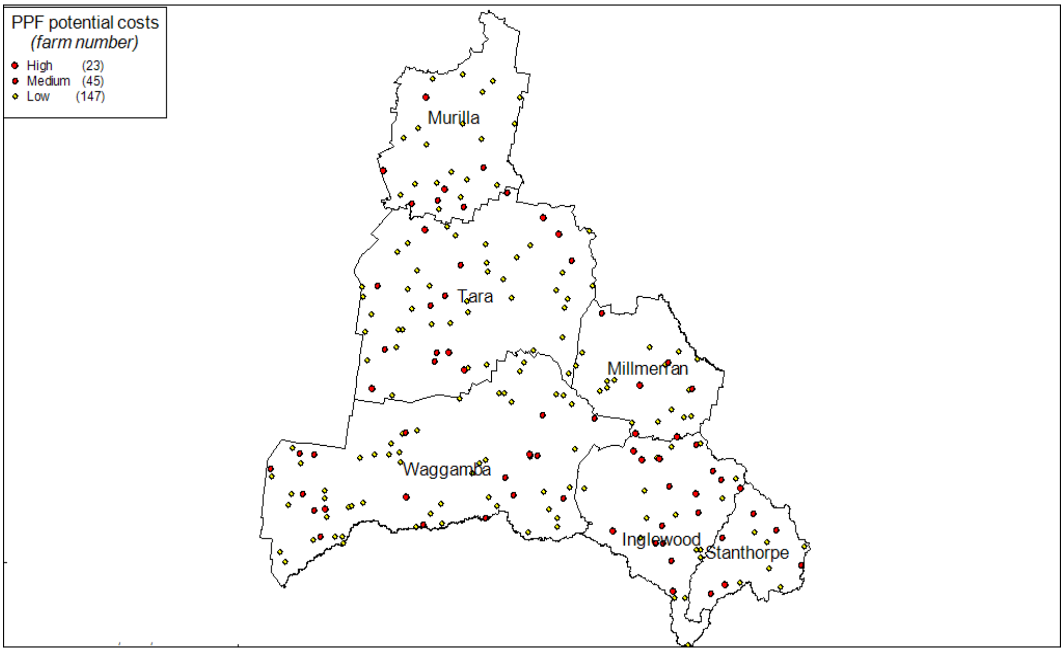


Table 11: Potential cost of PFF in the Border Rivers Naranoa-Balonne region ($) (*most likely value*)

Commodity	PFF cost	Market accesses loss	Net Present Value: Benefit of eradication
Apples	$1,654,900		$21,010,800
Tomatoes	$49,400		$627,200
Grapes	$78,500	$108,100	$2,369,500
Capsicums	$22,500		$285,800
Others	$252,900		$3,211,500
Total	$2,058,300		$27,504,800
Total	$1,958,700	$2,356,800	$54,790,200

1.5 Potential cost of PFF in Queensland

Table 12 summaries the estimated results of all potential PFF costs in QLD. The average nominal cost per year caused by a PFF incursion is $16.1 million and the total net present value over 25 years is $231.9 million. PFF costs are the most significant for the Wet Tropic areas, of which the cost to the banana industry is about $88 million over a period of 25 years, or roughly 38 per cent of the State's total potential PFF costs.

Table 12: Potential costs of PFF in Queensland by region ($)
(*most likely value*)

Commodity	PFF cost	Net Present Value: Benefit of eradication*
Wet Tropic	$6,754,300	$105,989,100
Burdekin	$1,311,000	$19,981,500
Burnett Mary	$4,315,500	$54,790,300
Border Rivers Naranoa -Balonne	$2,166,400	$27,504,800
South West	$429,700	$5,456,100
Fitzroy	$489,600	$7,034,100
Others	$713,000	$11,188,800
Total	$16,179,500	$231,944,700

*Note: *Total sum of benefits of PFF eradication over a lifetime project of 25 years.*

The values for potential costs in Table 12 are based on average values, including costs per hectare for eradication and yield losses. Clearly these values can vary. Applying Monte Carlo methods, with 5000 simulations, the distributed values of potential PFF costs are estimated with an assumed normal distribution. Over the period of 25 years, at a 90 per cent confidence interval the potential cost of PFF ranges from $214 million to $230 million, with the average value of $231 million (in 2015 prices).

1.6 Closing remarks for Papaya Fruit Fly

The Asian papaya fruit fly is a serious pest that could enter Queensland though the Torres Strait as a pathway. An establishment and spread that could cause significant economic losses for host horticultural industries.

The major horticultural areas, which are under a potential threat of PFF, are the Wet Tropic region, the Burnett Mary region, the Burdekin region, the Border Rivers Naranoa–Balonne, the Southwest, the Fitzroy and the Northern regions. There were about 2000 potential PFF host farms located in QLD in 2013. The average nominal cost per year caused by a potential PFF incursion is estimated at $16.1 million and total net present value over 25 years is $231.9 million. PFF costs are most significant for the Wet Tropic areas ($105 million). The cost of PFF to the banana industry is highest at about $88 million over a period of 25 years (representing 38 per cent of the state's total PFF costs). The potential cost of PFF in the Burnett Mary region alone is about $54.8 million. In terms of optimal local surveillance, it appears that the current surveillance grid used for the early detection of PFF in QLD is too large, with insufficient resources directed at this activity.

2 Citrus Canker

Citrus canker (*xanthomonas campestris*) (CC) is a highly contagious bacterial disease of citrus trees and related varieties, including grapefruit, lemons, limes and oranges. It reduces the growth of new fruit and spoils healthy fruit. The disease affects any part of the citrus tree growing above the ground, producing warty, rust-brown spots (cankers) on the leaves, twigs, shoots and the fruit of the trees (DAFF of Queensland 2015). Growth of young trees can also be severely affected due to damage to new shoots (Quarantine of South Australia 2013). According to Dewdney and Graham (2014), major citrus canker outbreaks generally occur when new shoots are emerging or when fruit are in the early stages of development, especially if a major rainfall event occurs during this critical time. Frequent rainfall in warm weather, especially when combined with bad storms, contributes to disease development. Citrus canker is mostly a 'cosmetic disease', but at high contamination levels the disease can cause defoliation, shoot die-back, and fruit drop.

Citrus canker is believed to have originated in the area of Southeast Asia and India. At present, the disease is in Japan, South and Central Africa, the Middle East, Bangladesh, the Pacific Islands, a few countries in South America, and in Florida. Some areas of the world have eradicated citrus canker and others have ongoing eradication programs, but the disease remains endemic in most areas where it has appeared. Given its rapid spread, high yield losses and resulting falls in sales in export and domestic markets, citrus canker is a significant threat to all citrus-growing regions (Das 2003). The cost of citrus canker is especially significant in countries and regions with large citrus industries, such as Brazil and in Florida.

In Brazil, citrus canker was first reported in 1957, in the state of Sao Paulo, the world's largest sweet orange area. At present, over 100,000 groves with about 2 million trees are in the state. Approximately 80 per cent of planting area is devoted to a single sweet orange variety that is highly affected by canker, with large associated economic losses. An eradication program is currently underway to manage the disease. Under the current eradication strategy, which has been applied since 1999, all citrus blocks in counties at a high risk of infestation are inspected more than once a year. Contaminated blocks are simultaneously observed by three inspection teams. All trees in the block are eradicated if more than 0.5 per cent of trees are infested. If 0.5 per cent or less of the trees are infested, the affected trees and nearby trees (within a radius of 30 meters) are eradicated. From January 1999 to December 2008, a total of 4.39 million citrus trees were eradicated in commercial blocks, with additional losses of 2.3 million trees, and 1.2 million trees, in citrus nurseries and non-commercial blocks, respectively. The total estimated damages and control costs caused by citrus canker here are approximately 476 million dollars (Bassanezi et al. 2009).

In the United States, citrus canker was first found in 1910 not far from the Georgia–Florida border. Subsequently, the disease was discovered in 1912 in Dade County, more than 600 km away, indicative of its rapid spread. The eradication took more than 20 years (from 1914 through 1931) at a cost of A$38 million in 2015 dollars (using the inflation index estimates by the US Department of Labour 2015). Citrus canker was detected again on the Gulf Coast of Florida in 1986 and declared eradicated in 1994. The most recent outbreak of citrus canker in the United States was discovered in Miami, Dade County, Florida, in Sept 1995. Despite efforts to eradicate the disease, by late 2005, it had been detected in numerous locations far from the original detection point. In January 2000, the Florida Department of Agriculture adopted a policy of removing all infected trees and all citrus trees within a 1900 feet radius of an infected tree (0.6 km). The program ended in January 2006 following a statement from the USDA that eradication was not feasible.

The citrus industry is an important horticultural industry in Queensland, accounting for more than \$81 million of the gross value of production in 2012–13 (ABS 2014a). In Australia, the citrus industry is the largest fresh fruit exporter valued at about A\$200 million annually (ABS 2014a). At present, citrus canker is an exotic disease in Australia. Previous outbreaks have been eradicated from the Northern Territory and, more recently, in Queensland. However, after a successful eradication in 2009, the disease was detected again in 2013. This highlights the need to maintain a high level of vigilance to detect future disease outbreaks early enough to eradicate them and thereby prevent the disease becoming widespread in Australia. An outbreak of citrus canker has the potential to devastate Queensland's citrus industry, reflecting the fact that the disease can spread rapidly and result in large economic losses from yield declines and lost market access. Even where eradication efforts begin early enough to be successful, the cost of the eradication programs can be substantial, with the most recent successful program at Emerald imposing large costs on growers, associated industries and government (Department of Primary Industry (DPI) of Queensland, 2014).

2.1 Citrus canker and citrus production

According to the Department of Agriculture (2015), citrus canker is wide-spread in many tropical and subtropical citrus-growing areas of the world. Citrus canker can be spread over long distances on equipment (e.g., vehicles, tools, mechanical hedgers, sprayers, gardening equipment) and by people (e.g., hands, shoes and clothing). Movement of infected plant material, or airborne movement of bacteria as an aerosol or debris during severe weather events (i.e., when strong winds and rain are present), are additional vectors for disease spread. Illegal importation of infected plant material also poses a great risk of introducing this disease into Australia. The largest contributing factors in the spread of citrus canker include contact by grove workers, equipment, and wind-driven rain. Contact by grove workers or the equipment used by grove workers can spread the disease to other groves. Equipment such as ladders, sprayers, and trucks can readily become contaminated and spread the disease to other trees in neighbouring groves.

As mentioned, citrus canker, is a common disease in most overseas citrus growing regions, and although Australia's physical isolation has been an effective barrier to the disease, occasional outbreaks occur. Australia has had three outbreaks of citrus canker, all of which were successfully eradicated. The disease was found twice during the 1900s in the Northern Territory and was eradicated each time. The most recent outbreak, which occurred in central Queensland in 2004, appears likely to have resulted from importation of infested stock. Australia is currently free of citrus canker.

The 2004 outbreak involved an initial detection in Emerald, Queensland (IP1). Ten months later, it was detected on two other farms (IP2 and IP3) within the same area. The oldest, naturally infected plant tissue observed on any of these farms indicated that the disease was present on IP1 for several months before detection, and established on IP2 and IP3 during the second quarter (Gambley et al., 2013). However, these facts are inadequate for modelling CC spread by time, area and climate. Even the issue of CC density has been challenged. Based on Gambley et al. (2013), transect studies on some IP1 blocks showed disease incidences ranging between 52 and 100 per cent of trees. At the time, the State and Federal governments ordered all commercial groves, all non-commercial citrus trees, and all native lime trees (*C. glauca*) in the vicinity of Emerald to be destroyed. The Queensland outbreak (2004) was eradicated through bulldozing and burning affected trees, at great cost to industry and government (Quarantine of South Australia 2013). Eradication costs were \$17.8 million and \$9 million paid to assist affected growers (Senate Standing Committees on Rural and Regional Affair and Transport 2009). Australia was declared free of citrus canker in 2009. However, an outbreak of CC was detected in the Northern Territory in 2013, increasing concerns about the risk of future outbreaks in Australia.

2.2 Citrus production and export markets for Australia and Queensland

2.2.1 Citrus production in Australia

According to Citrus Australia (2014), Australian citrus production began in 1787 when the English First Fleet sought to introduce sustainable horticulture to Australia. Lemons, limes, oranges, grapefruit and mandarines were planted in and around Sydney and formed the first step in the development of the citrus industry. The early settlers found Australia's diverse climate ideal to produce a large range of high quality citrus fruits. In the southern growing regions, hot, dry summers and cool winter rains encourage high-quality orange fruit growth and exceptional colour. Citrus production in Australia provides roughly $481.4 million of gross value of production and $384.6 million of farm gate value (Table 13). At present, approximately 28,000 hectares of citrus are planted by around 1,900 growers (Table 14). Citrus production in Australia tends to be highly concentrated in the inland irrigation regions. The major production regions are in the Riverland of South Australia, Victoria's Murray Valley, the Riverina of New South Wales and the Central Burnett region in Queensland (Table 14). There also are additional plantings throughout Western Australia, inland and coastal New South Wales, other regions in Queensland, as well as smaller plantings in the Northern Territory.

Based on Aussie Orange (2014), citrus production volumes are largest for oranges (76 per cent), followed by mandarines (16 per cent), lemons and limes (5.5 per cent) and grapefruit (2.5 per cent). In 2012–13, the gross value of mandarine and orange production was about a half-billion dollars (ABS 2014a) (Table 13).

Table 13: Gross values of citrus production in Australia *(A$ million)*

Commodity	Gross value ($A\$mil$)	Local value ($A\$mil$)
Mandarins	153.6	126.5
Oranges (navel, Valencia and other)	345.9	270.0

Source: Australian Bureau Statistics (ABS), 2014a.

2.2.2 Citrus growing regions and export markets in Australia

Table 14 reports key citrus production statistics by region. Queensland has combined citrus plantings totalling approximately 3,590 hectares and is the largest producer of mandarines (particularly Imperials and Murcotts) in Australia. Major growing regions include the Central Burnett (Gayndah and Mundubbera districts), Emerald, Bundaberg and Mareeba.

The Northern Territory has experienced a decline in citrus plantings over recent years, reflecting an increase in the popularity of mangoes. Plantings are based around the Darwin and Katherine areas and consist mainly of Eureka and Lisbon lemons and Star Ruby grapefruit. Total citrus plantings amount to about 135 hectares in area.

The Riverland region of South Australia, with about 6300 hectares of citrus plantings, is the third largest growing region in Australia. The main varieties grown are navels (predominately

Washington), Valencia oranges and mandarines (Imperial and Afourer). Citrus is grown primarily in the Riverina (Griffith, Leeton and Hillston districts), central NSW (Moree, Gunnedah, Bourke, Narromine and Forbes) and the east coast of NSW (Gosford and Lismore regions).

Citrus is one of the most important horticultural industries in NSW with a production area of around 13,000 ha. The state produces around 250,000 tonnes of citrus annually, representing 40 per cent of Australian production and 36 per cent of citrus exports (Citrus Australia 2014 and Horticulture Australia 2013).

Table 14: Production by citrus growing regions

	Area of planting *(ha)*			Number of planting *(thous trees)*			Properties	Density *(tree/ha)*
	2003	2008	2011	2003	2008	2011	2010/11	2010/11
Riverina NSW	8,317	8,480	8,800	3,314	3,457	3,586	474	407.5
Murray Valley	7,128	6,569	6,580	3,144	3,084	3,095	477	470.4
Riverland SA	7,327	6,303	6,303	2,917	2,747	2,747	557	435.8
Queensland	4,645	3,850	3,591	1,904	1,561	1,483	84	413.0
Western Australia	1,042	1,356	1,561	464	672	813	184	520.8
Central NSW	638	643	875	344	373	516	15	589.7
East Coast NSW	555	403	368	325	231	202	69	548.9
Northern Territory	233	206	137	83	73	48	7	350.4
Total	29,885	27,810	28,216	12,495	12,197	12,490	1,867	442.7

Source: Australian Bureau of Statistics, 2014b.

The export value of citrus in Australia is approximately A$200 million (ABS 2014a), primarily from mandarine and orange exports. An important target for industry is to improve and fast-track phytosanitary (quarantine) and non-phytosanitary (non-quarantine) market access into key countries such as China, the Republic of Korea, Japan, Thailand, Indonesia and the USA (Citrus Australia 2014). Efforts to improve access to these markets would be substantially set back by an outbreak of citrus canker in Australia. Key statistics of citrus production by state and major export markets for Australian oranges and mandarines are reported in Tables 15–17.

Victoria was the largest orange exporter, accounting for almost half of the nation's orange exports in 2011–12, with South Australia and New South Wales also being major orange exporters (Table 15). In 2011–12, the most important export markets for oranges were Japan, Hong Kong, Malaysia and Singapore. Japan, Hong Kong, Malaysia accounted for about 53 per cent of total orange export destinations in 2011–12 (Table 16).

Table 15: Orange export by state *(ton)*

State	2007/08	2008/09	2009/10	2010/11	*2011/12
Victoria	46,907	41,857	52,510	32,015	43,680
South Australia	42,311	42,084	44,504	31,721	39,105
New South Wales	26,682	24,203	33,022	20,443	20,005
Queensland	1,026	1,377	1,462	1,476	1,557
Tasmania	22	-	-	3	-
Western Australia	11	24	-	-	-
Northern Territory	-	-	0.2	-	1
Total	116,960	109,545	131,498	85,657	104,348

Source: Horticulture Australia 2013 based on Global Trade Information Services (GTIS)
Notes: May include re-export data, resulting in variance with total export by state.
** 2011/12 covers the period July 2011 to May 2012.*

Table 16: Major Australia's orange export markets *(ton)*

Importing Country	2007/08	2008/09	2009/10	2010/11	2011/12
Japan	14,310	13,957	17,713	28,621	21,151
Hong Kong	24,870	19,351	21,302	15,708	18,961
Malaysia	9,210	15,633	12,663	4,268	15,006
Singapore	5,544	9,119	8,093	4,643	8,947
United States	26,526	20,426	25,526	11,276	6,870
United Arab Emirates	8,252	6,448	9,692	2,702	6,490
India	1,197	2,017	5,830	2,286	4,264
New Zealand	4,707	5,488	5,863	3,179	3,486
Indonesia	2,793	3,245	4,004	3,099	3,101
Canada	3,349	3,183	3,154	3,224	2,964
Thailand	530	687	1,273	1,362	1,073
Others	15,677	9,992	16,384	5,297	12,184
Total	116,964	109,545	131,498	85,665	104,497

Source: Horticulture Australia 2013 based on Global Trade Information Services (GTIS)

In 2011–12, Queensland was the most important state for mandarin exports, accounting for more than half of the nation's mandarin exports. Victoria and South Australia are also the major states for mandarin exports. While orange export markets are very much dominated by Japan, Hong Kong and Malaysia, a number of countries are substantial export destinations for mandarines. In 2011–112, the most important mandarine exporter markets were in Indonesia, United Arab Emirates, Hong Kong and New Zealand (Table 17).

Table 17: Major Australia's mandarin export markets *(ton)*

Importing Country	2007/08	2008/09	2009/10	2010/11	2011/12
Indonesia	2,173	3,475	3,539	3,290	4,168
United Arab Emirates	1,766	2,700	2,863	2,806	4,154
Hong Kong	3,921	2,780	5,708	3,311	4,067
New Zealand	2,204	2,712	3,094	3,091	3,674
Thailand	142	67	730	1,706	2,526
Japan	1,225	1,399	1,016	1,131	2,102
United States	4,242	3,722	4,040	2,095	2,079
Singapore	441	953	1,304	1,009	1,360
Taiwan	586	1,446	2,683	2,268	1,042
Others	3,807	4,001	5,743	3,638	4,511
Total	20,506	23,253	30,721	24,346 29,682	

Source: Horticulture Australia 2013 based on Global Trade Information Services (GTIS).

2.3 A basic spatial bioeconomic modelling approach to the potential cost of a citrus canker spread

The approach taken to estimate the benefits and costs of citrus canker is based on a basic spatial bioeconomic model. The approach, which we previously applied to evaluate programs aimed at early detection of papaya fruit fly (see Section 1 above), and the eradication of red imported fire ants (Hafi et al. 2014), combines geographic information, pest/disease spread dynamics and spatial economic parameters. The approach allows us to combine environmental, biological and economic knowledge in estimating the spread of the disease and its spatial impacts over time. This information, in turn, can be used to determine an effective strategy for allocating resources available for citrus canker monitoring and control.

2.3.1 Spatial growth of citrus canker

As in Section 1, the spatial and temporal modelling generally follows Lopes et al. (2008) and our simulations are guided by material in Vose (2000). Our work is also informed by results developed by Gottwald et al. (2007), who studied the spread of citrus canker in Sao Paulo (Brazil). The population (measured as infested farms) of CC will grow from location to location, and time to time. At time at $t+1$, the infested farm (N) of PFF at location s is given by

$$N(t+1, s(\vec{x}_{t+1}, \vec{y}_{t+1})) = F[p_{ij}, \mu(t)^{N^*}, \beta(s(\vec{x}_{t+1}, \vec{y}_{t+1})), f(t), \xi] \quad (18)$$

where the PFF infested population $N(t{+}1)$ is two-dimensional vector of locations $s(x, y)$ (*where*) and time (t=1-T) (*when*); $f(t)$ and $\beta(s(\vec{x}_t, \vec{y}_t))$ characterises movement over time and space; $\mu(t)^{N^*}$ is a simulated dynamic over time and space; and ξ represents uncertainty.

The population of infested farms at time $(t+1)$ and space j follows an assumed logistic function given by

$$N_{t+1,j} = N_{1,j} + r_j \left[1 - \frac{N_{tj}}{Nmax}\right] - m_{tj}N_{tj} \tag{19}$$

where the spatial domain (s) is subdivided into a set of discrete patches j to Ω; r is the growth rate of PFF; $m_{tj}N_{tj}$ is infested areas reduced by management m_tj; and $Nmax$ is maximum carrying capacity.

2.3.2 Cost function of citrus canker in infested citrus farms

The spatial economic impact caused by the spread of CC depends on the spatial-temporal factors governing population spread and relevant economic parameters. The economic parameters that determine the magnitude of potential costs caused by CC can vary by time and space. Citrus canker would have multiple effects on the Australian citrus industry, including yield and market access losses and, at the least, a resulting lower price for any fresh fruit sold in premium (export) markets (Spreen et al. 2003).

Although fruit infected with citrus canker is not harmful, the disease can inflict substantial costs on growers by reducing the proportion of fruit that is suitable for the fresh market. Citrus canker can also diminish the productivity and vigour of affected trees leading to a reduction in fruit yields. It is estimated that fruit from canker-affected trees will reduce pack-out rates by as much as one-third for the fresh market. Experience with this disease in other countries suggests that yield losses will range from 5 to 30 percent, depending upon the scion (variety). Some citrus varieties are more susceptible to canker than others. For example, grapefruit varieties are more vulnerable to canker lesions than some varieties of oranges, such as Valencia oranges. It has been estimated that in Florida, increased fruit drop arising from CC infestation in early and mid-season oranges and seedless grapefruit ranges from 5–10 per cent annually. For Valencia oranges, the increase in fruit drop could be 2–5 per cent annually. The drop rate could be up to 30 per cent higher than normal under an ineffective citrus canker control program, involving sub-optimal timing of copper spray applications (Muraro et al. 2003).

The losses in yields and market access caused by CC are given by

$$C_{t+1,j} = \overbrace{N_{t+1,j}y_{loss,j}p_j}^{Yield\,loss} + \overbrace{N_{t+1,j}(1 - y_{loss,j})M_j(p_j - p_2j)}^{Market\,access\,loss} \tag{20}$$

where y_{loss} is the yield loss of variety j at time $t+1$; p_j is the price of citrus j; p_{2j} is the market loss caused by lower price of citrus after a canker outbreak in fresh fruit markets; and M_j is the market share of citrus j in total production. The average yield loss, which depends on fruit variety and canker density, is given by

$$y_{loss,j} = (w1l_{max} + w2l_{med} + w3l_{min}) \tag{21}$$

where $w1$, $w2$ and $w3$ is the share of average yield loss by maximum (l_{max}), medium (l_{med}) and minimum levels (l_{min}), respectively.

In this case study, measures of uncertainty are set for yield loss and citrus farm gate value with minimum, most likely and maximum values (see Table 18). Approximation of potential costs are obtained from trial simulations, using different sets of random variation. An comparable example of this technique for analysing citrus market under uncertainty is provided in McClain (1989). As with PFF, we simply combine a spatial mapping (GIS) tool with an assumed logistic growth model, given parameters for spread, prices and costs of CC. Parameter values are as indicated. To visualise, we map infected farms, using MapInfo, month-by-month, randomly simulated based on the number of farms located in an area, given an assumed initial outbreak.

2.3.3 Key assumptions and parameters

There are a number of key assumptions used in this report. The local value of horticulture (i.e., 'Local Value'), or the value placed on recorded production at the place of production, including indirect taxes, and calculated by subtracting total marketing costs from gross value (ABS 2014a), is used as the direct farm value rather than Gross Value of Production (GVP). It is assumed that the disease impacts would occur only at the farm level, by directly affecting citrus. Due to lack of available parameters, indirect impacts such as transportation costs, consumer perceptions of fruit quality and other potential industry-wide effects are not estimated. A second assumption is that the states or area facing the highest risk from a CC outbreak are Queensland, the Northern Territory and New South Wales, reflecting their suitable climate for CC development. A third assumption is that citrus canker cannot exist in areas with climatic conditions that are unsuitable for CC development, such as deserts).

In this report, our analysis of the economic costs of CC in Australia focuses only on Queensland and New South Wales, rather than all states or areas that could potentially be affected by CC. This reflects the fact that a citrus canker outbreak is probably most likely to begin in Queensland. If eradication in this state is unsuccessful, it is hoped that it is also unlikely that the disease would spread beyond Queensland and become endemic in NSW, Victoria and South Australia within the 15 year time horizon we consider. This assumption is worth further examination.

Other key assumptions and parameters used in this report, based on Dewdney and Graham (2014), Spreen et al. (2003), Muraro (2003), Bassanezi et al. (2009) and the known facts of disease outbreaks in Australia, include:

- Areas of highest risk from a CC outbreak are areas where citrus is grown in Queensland (and New South Wales).
- The potential costs arising from a CC outbreak are largest in regions with the largest density of citrus production, including, for example, the Burnett Mary region in Queensland.
- It would take the disease five years to spread over the entire Burnett Mary region, without eradication efforts.
- The next citrus canker outbreak is likely to occur in over a 1:15 year period, based on CC incidence reports in Australia. Accordingly, a time horizon of 15 years was selected for our analysis.
- A typical CC outbreak would affect up to 70 per cent of trees in areas where the disease is present.

- Future citrus production and production values are assumed to be unchanged from current values. Values of citrus industries are taken in years 2012–13, drawn from the ABS (2014a).
- The discount rate for this analysis is 0.03/year.
- Key parameters governing the magnitude of the economic impacts arising from a CC outbreak in Queensland (see Table 18) are based on previous studies of citrus canker development, including Spreen et al. (2003), Bassanezi (2009) and Gambley (2009), as well as on the specific geological and economic attributes of Queensland. Minimum and maximum farm gate values are a simple 5 per cent deviation with the most likely value, which is derived from the ABS (2014a,b).

Table 18: Key parameters for economic estimation of citrus canker in Australia

Parameters	Unit	Value
Time length for endemic	$year$	5
Initial infested area	$farm$	1
Yield loss	%	
Minimum		5
Most likely		15
Maximum		30
Citrus farm gate value	$(A\$/kg)$	
Minimum		1.14
Most likely		1.2
Maximum		1.26
Export market share	%	30
Lower price of export fruit	%	15
Discount rate	%	3

2.4 Estimated citrus canker costs in Queensland

2.5 Citrus production in Queensland

The citrus planting area in Queensland is about 2,500 ha, of which the main production areas are Mundubbera and Gayndah in the Central Burnett and in Emerald. Minor production areas include Bundaberg, Howard, Mareeba, Maryborough and the Sunshine Coast. Figure 17 presents citrus areas in Queensland, including the high value of citrus area Burnet Mary and other low value of citrus areas, which accounts for 94 per cent and 6 per cent of the state's citrus gross value in 2012–13, respectively (ABS 2014a).

The Burnett Mary region has the largest area of mandarine production, accounting for 98 per cent of production and gross value in 2012–13 (Table 19). Mandarines, primarily comprising Imperials and Murcotts, are the main citrus fruit grown in Queensland, accounting for 94 per cent of the gross value of production in 2012–13 (Table 19). Other citrus varieties grown in Queensland are oranges, lemons, limes and grapefruit. Most fruit is grown for the fresh fruit market, but a small proportion of the orange crop is used for juice production.

Fruit is harvested from about January to October with the bulk of the crop picked between March and July. Most of the fresh fruit produced is marketed in the major metropolitan wholesale markets of Brisbane, Sydney and Melbourne, but a large and increasing amount of the mandarine and orange crop is exported (DPI of Queensland, 2014). In 2012–13, about 30 per cent of mandarine production was exported (Horticulture Australia 2013).

Figure 17: Major citrus areas in Queensland

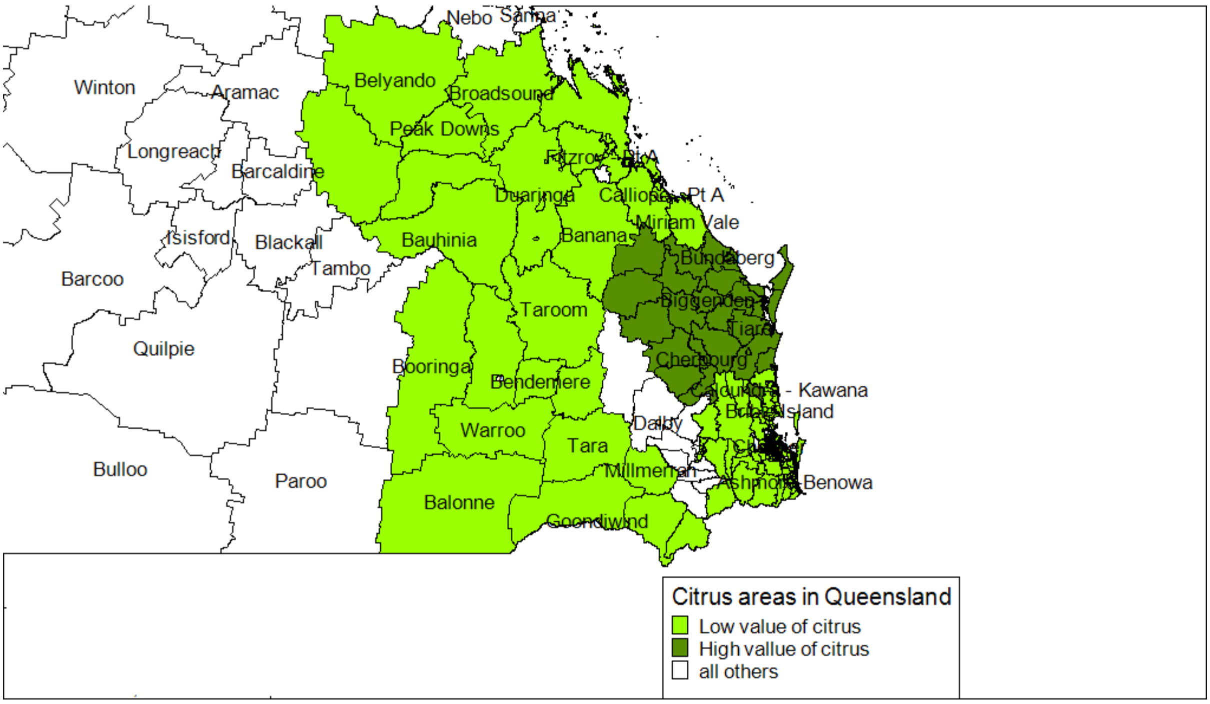


Table 19: Citrus production in Queensland, 2012–13

Contents		Queensland	Major citrus areas				
			Balonne -Maranoa	Burnett Mary	Cape York	Fitzroy	South East
Production	*ton*	55,462	875	54,340	2	225	20
Total trees	*no*	1,198,838	30,000	1,016,307	38	18,900	2,658
Yield	*kg/tree*	51.9	29.2	53.5	50.3	11.9	7.5
		Value of citrus production					
		Mandarins					
Gross value	*$ mil*	78.21	1.23	76.63		0.32	0.03
Local value	*$ mil*	64.73	1.02	63.42		0.26	0.02
		Oranges					
Gross value	*$ mil*	3.21	2.42				
Local value	*$ mil*	2.38	1.8				

Source: Australian Bureau of Statistics, 2014a,b.

2.5.1 Estimated citrus canker costs in Queensland

The potential cost of a citrus canker outbreak is estimated using Monte Carlo methods involving 5000 simulations. The initial outbreak is assumed to occur in the Burnett Mary region, where the potential cost of a CC outbreak is (likely to be) greatest. Estimated costs of citrus canker over the 15–year period of analysis, at a 90 percent likelihood, range from A$74 million to A$89 million (in 2015 prices). Table 20 presents the most likely values of citrus canker costs in 2015 prices for Queensland and and the Burnett Mary region over a time horizon of 15 years. On average, citrus canker could cost Queensland about A$7.1 million per year when the disease becomes endemic.

2.5.2 Case study of the Burnett Mary region

Given the importance of the Burnett Mary region as a citrus producing region, which accounts for more than 95 per cent of citrus gross value in QLD, this section focuses on the potential cost of CC spread in this region. There are 192 citrus farms located in the Burnett Mary region, including 105 mandarin farms and 87 orange farms (ABS 2014b). The economic value of citrus growing farms is represented in Figure 17. On average, the farm gate value of mandarin and orange farms is A$720,000–725,000 and A$220,000 per farm, respectively. Using Mote Carlo simulations, the estimated potential costs of citrus canker in this region are estimated. The cost of citrus canker, if it is not controlled, would range from A$6.3–7.6 million per year at 90 per cent confidence interval, with the most likely value of about A$6.9 million.

The spread of citrus canker over time is illustrated in Figures 19–20 with the potential cost of yield and market access losses reported in Table 21. If CC becomes endemic for all 193 farms at year 5 (see Figure 20), the potential cost caused by CC would be up to A$6.8 million per year, with roughly 82 per cent from yield loss and 18 per cent from market access losses.

Table 20: Estimated citrus canker cost in Queensland and the Burnett Mary region *(most likely Net Present Value (NPV) in A$ thousand)*

Year	Net Present Value of citrus canker cost	
	Queensland	Burnett Mary
0	160	157
1	350	343
2	765	751
3	1,672	1,639
4	3,652	3,580
5	7,975	7,818
6	7,743	7,591
7	7,517	7,370
8	7,298	7,155
9	7,086	6,947
10	6,879	6,745
11	6,679	6,548
12	6,484	6,358
13	6,296	6,172
14	6,112	5,993
15	5,934	5,818
Total	82,604	80,982
Average per year after endemic	6,909	6,774

Figure 18: Citrus values in the Burnett Mary region, Queensland

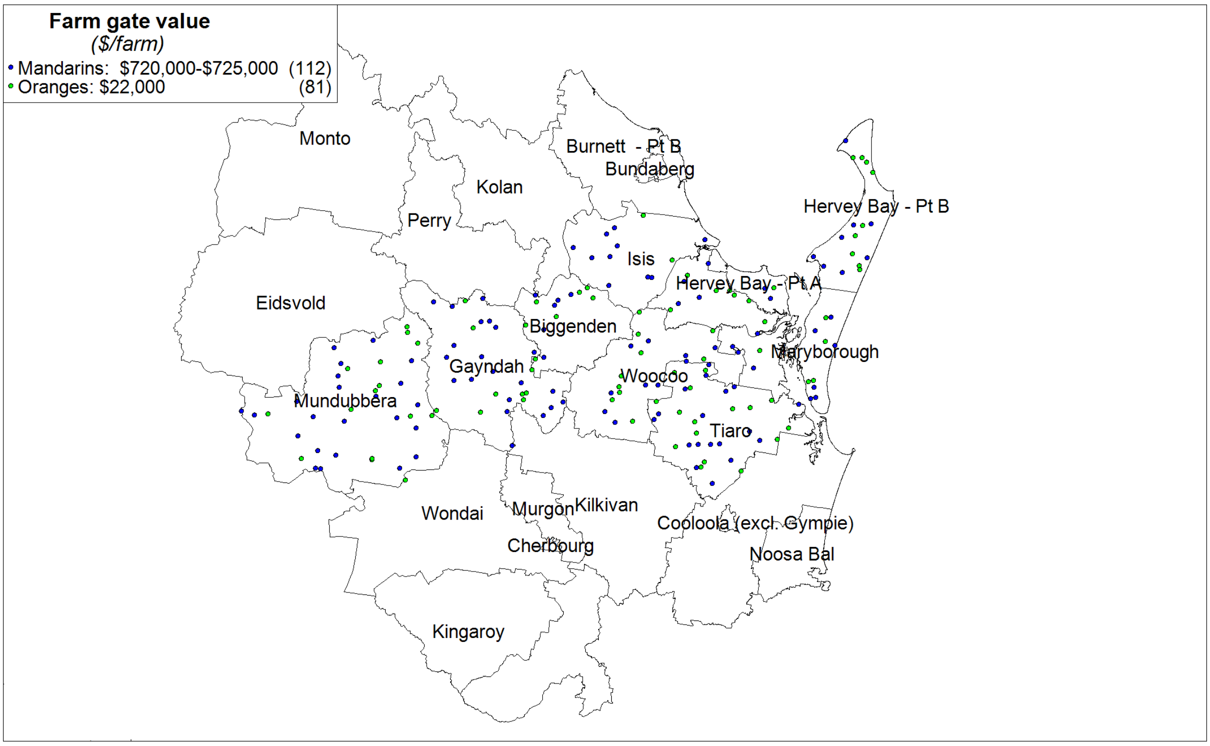


Figure 19: Simulation of the spread of citrus canker in the Burnett Mary region: Year 3

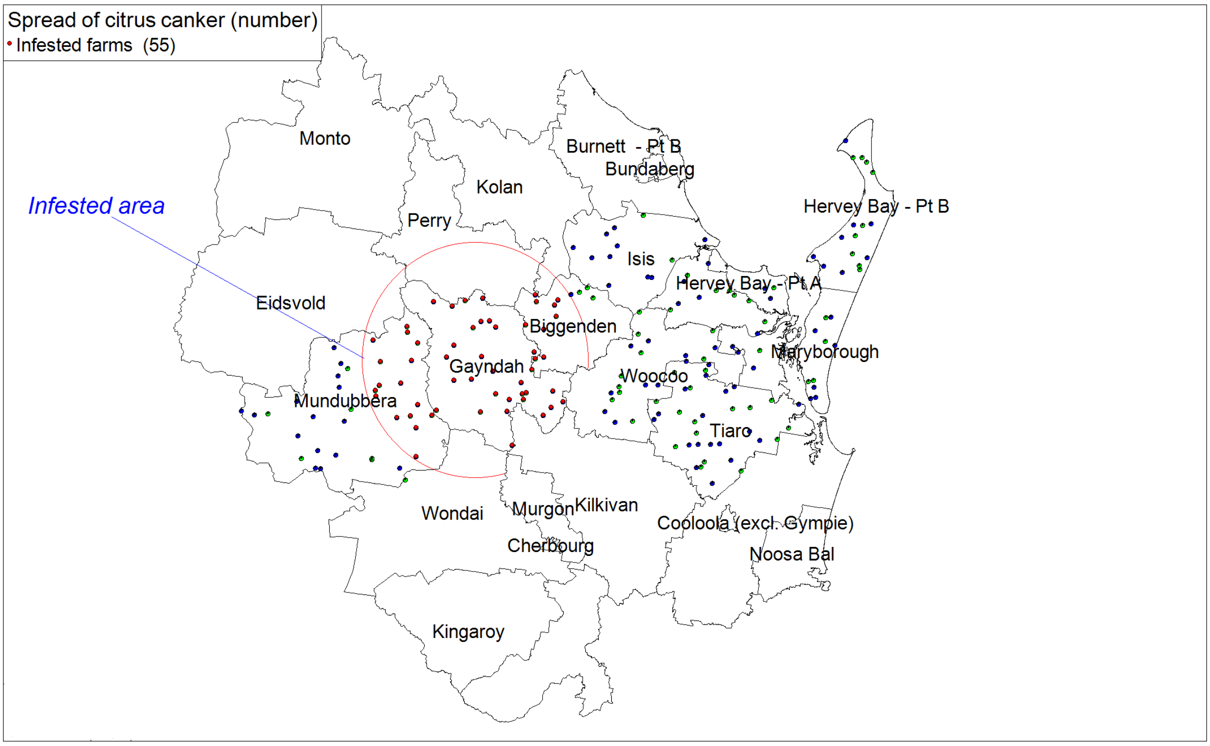
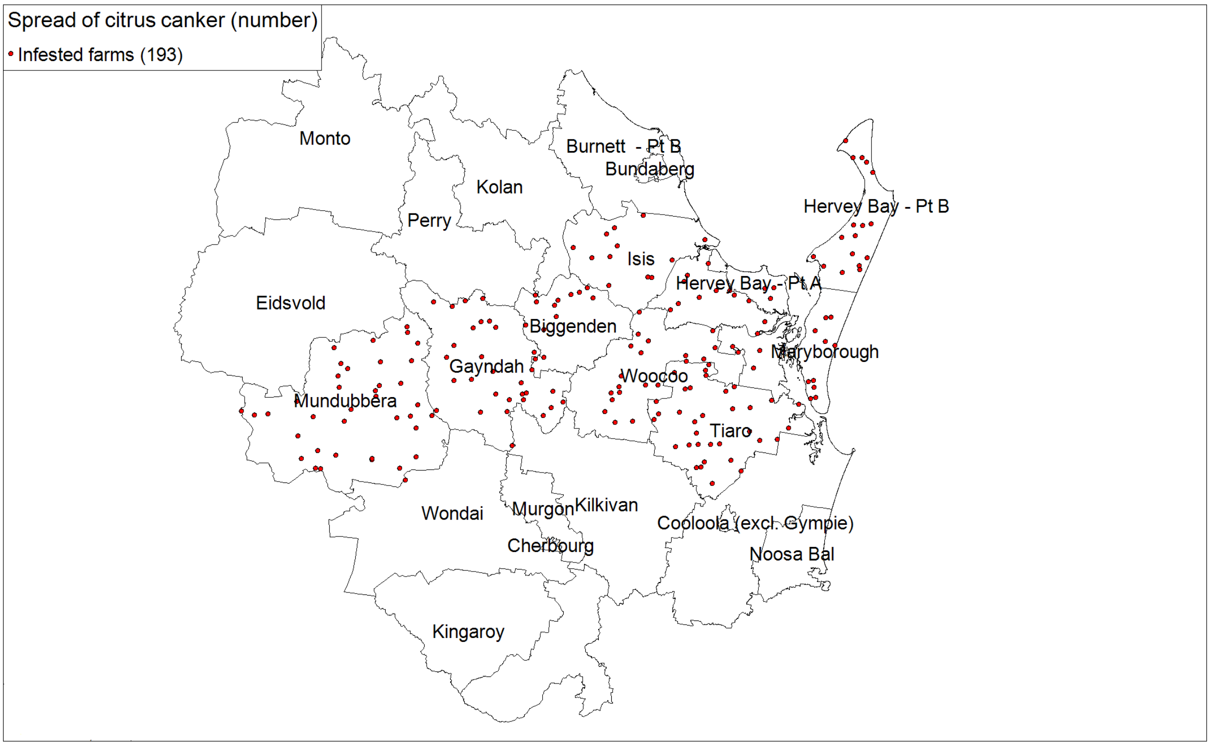


Table 21: Costs of citrus canker threat in the Burnett Mary region *(most likely net present value in A$ thousand)*

Year	Cost contents		Total cost
	Yield loss	Market access loss	
0	128	29	157
1	280	63	343
2	613	138	751
3	1,338	301	1,639
4	2,922	658	3,580
5	6,382	1,436	7,818
6	6,197	1,394	7,591
7	6,016	1,354	7,370
8	5,841	1,314	7,155
9	5,671	1,276	6,947
10	5,506	1,239	6,745
11	5,345	1,203	6,548
12	5,190	1,168	6,357
13	5,038	1,134	6,172
14	4,892	1,101	5,992
15	4,749	1,069	5,818
Total	66,108	14,874	80,892
Average per year after endemic	5,530	1,244	6,774

Figure 20: Simulation of the spread of citrus canker in the Burnett Mary region: Year 5



2.6 Estimated citrus canker costs in New South Wales

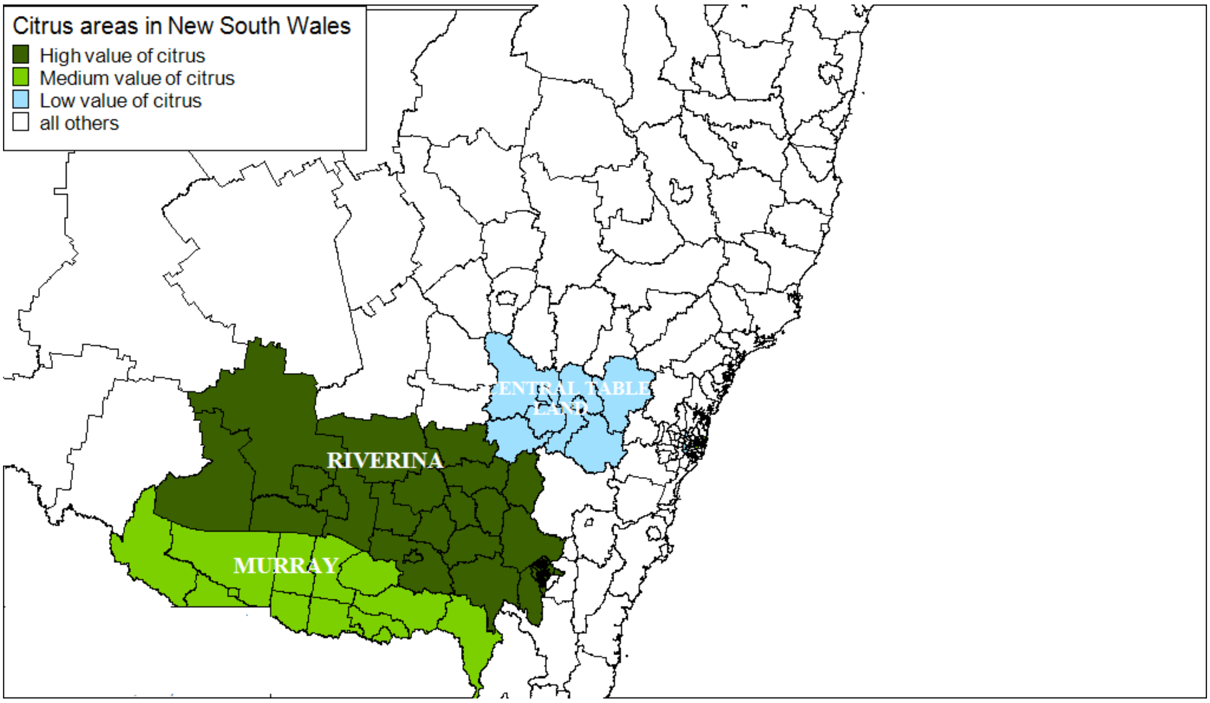
2.6.1 Background of citrus production in New South Wales

The major citrus producing areas in NSW are Riverina, Central Land and Murray, which accounts for 76.3 per cent, 21.2 per cent and 3 per cent of New South Wales's citrus gross value in 2012–13, respectively (see Figure 21) (ABS 2014a). The main citrus fruits grown in NSW are navel and Valencia oranges, mandarines, lemons, limes and grapefruit (Agriculture of New South Wales, Department of Primary Industries 2014).

The Riverina is the largest growing region in Australia. Over 50 per cent of the planted area has Valencia oranges and 40 per cent has navels (mostly Washington and Late Lane). Total citrus plantings in 2011 in this region is 8,800 ha (ABS 2014b).

Central NSW has significant plantings of common oranges (mainly Salustiana and Hamlin) in addition to Valencia and navel plantings. Total citrus plantings in this region were about 875 ha in 2011. The east coast predominantly grows Washington navels, Eureka lemons and Valencia oranges. The total area of citrus plantings in the east coast is about 365 ha. The Murray Valley growing region is the second largest growing district in Australia. In 2011, total plantings there were 6,580 ha, with 63 per cent of plantings being navels (predominantly Late Lane, Washington and Leng). This region also has significant plantings of Valencia oranges and Imperial and Afourer mandarines (ABS 2014b).

Figure 21: Major citrus areas in New South Wales



Tables 22 and 23 present key production measures, including tree numbers and yields, as well as economic values of the major citrus areas in NSW.

Table 22: Mandarin production by region, 2012–13

Contents		NSW	Major citrus areas			
			Lower Murray	Murray	Murrumbidgee	Northern Rivers
Production	*ton*	3,937	1,135	115	1,711	293
Trees	*no*	332,780	143,813	34,403	69,719	49,427
Yield	*kg/tree*	19.2	28.6	5.0	28.1	6.4
		Value of mandarin production				
Gross value	*$ mil*	7.71	2.22	0.2	3.35	0.6
Local value	*$ mil*	6.36	1.83	0.19	2.76	0.5

Source: Australian Bureau of Statistics 2014a,b.

Table 23: Orange production by region, 2012–13

Contents		NSW	Major citrus areas			
			Lachlan	Lower Murray	Murray	Murrumbidgee
Production	*ton*	206,961	38,856	38,469	5,155	119,023
Trees	*no*	4,125,134	670,700	739,231	98,919	2,259,267
Yield	*kg/tree*	52.5	57.9	55.5	52.9	55.9
		Value of orange production				
Gross value	*$ mil*	174.0	32.7	32.4	4.3	100.1
Local value	*$ mil*	135.5	25.5	25.2	3.4	78.0

Source: Australian Bureau of Statistics 2014a,b.

Most citrus production supplies the domestic market, with citrus export from NSW accounting for about 9.7 per cent of total citrus production in 2012–13, (Horticulture Australia 2013 and ABS 2014). As a result, the effect of CC on orange market access in infested areas would share a lower rate than mandarin in Queensland.

2.6.2 Estimated citrus canker costs in New South Wales

We considered a CC outbreak scenario in which the initial outbreak occurs in the Riverina, which is the location with the largest potential economic impact. Table 24 presents the key assumptions made in estimating citrus canker costs in NSW. The costs of citrus canker in NSW area are again estimated using Monte Carlo methods with 5000 stimulations. Over the 15-year period of analysis, at a 90 percent probability, the potential costs of citrus canker in NSW ranges from A$82 million to A$100 million (in 2015 prices), with the most likely value of about A$91 million.

Table 24 presents the mean values of citrus canker costs at 2015 prices for New South Wales and the Riverina region over a time horizon of 15 years. After the disease becomes endemic, on average, citrus canker could cost NSW about A$9.3 million per year, including A$8.4 million of yield losses and A$0.9 million of market access losses.

Table 24: Key parameters of economic estimation for New South Wales

Parameters	Unit	Value
Time length for endemic	*year*	9-10
Initial infested area	*farm*	1
Yield loss	%	
Minimum		5
Most likely		10
Maximum		20
Citrus farm gate value	$(A\$/kg)$	
Minimum		0.64
Most likely		0.67
Maximum		0.70
Export market share	%	9.7
Lower price of export fruit	%	15
Discount rate	%	3

Table 25: Mean value of net present value of citrus canker costs in New South Wales *(A$ thousand)*

Year	Net present value of citrus canker cost	
	New South Wales	Riverina
0	18	11
1	44	26
2	110	66
3	273	164
4	680	408
5	1,690	1,014
6	4,204	2,523
7	10,458	6,275
8	10,153	6,092
9	9,857	5,914
10	9,570	5,742
11	9,291	5,575
12	9,021	5,412
13	8,758	5,255
14	8,503	5,102
15	8,255	4,953
Total	90,886	54,531
Average per year after endemic	9,319	5,591

2.6.3 Case study of the Riverina region

The Riverina region is the most important citrus growing area in NSW, accounting for almost 60 per cent of total citrus production in 2012–13 (ABS 2014b). Figure 22 shows citrus values in the Riverina region based on ABS (2014a). There are 329 citrus farms located in the region, of which 313 farms are orange farms. The average farm gate value of orange farms is A$400,000. The number of mandarin farms and their farm gate values are relatively lower than orange farms. Using Mote Carlo simulations, the estimated potential costs of citrus canker in this region are estimated. The cost of citrus canker, if it is not controlled, would range from A$4.9 million to A$6.2 million (in 2015 prices). The most likely value of the cost is A$5.6 million.

The simulated spread of citrus canker over time is illustrated in Figures 23–24 with the potential cost of yield losses and market access losses reported in Table 26. If CC become endemic at year 9 (see Figure 24), CC would affect to all farms in the region. Using Monte Carlo methods with 5000 stimulations, at a 90 percent probability, annual costs of endemic CC in the Riverina range from $4.9 million to $6.2 million (in 2015 prices). The most likely value of the cost is $5.6 million, apportioned by 90 per cent from yield losses and 10 per cent from market access losses.

Figure 22: Citrus values in the Riverina region, New South Wales

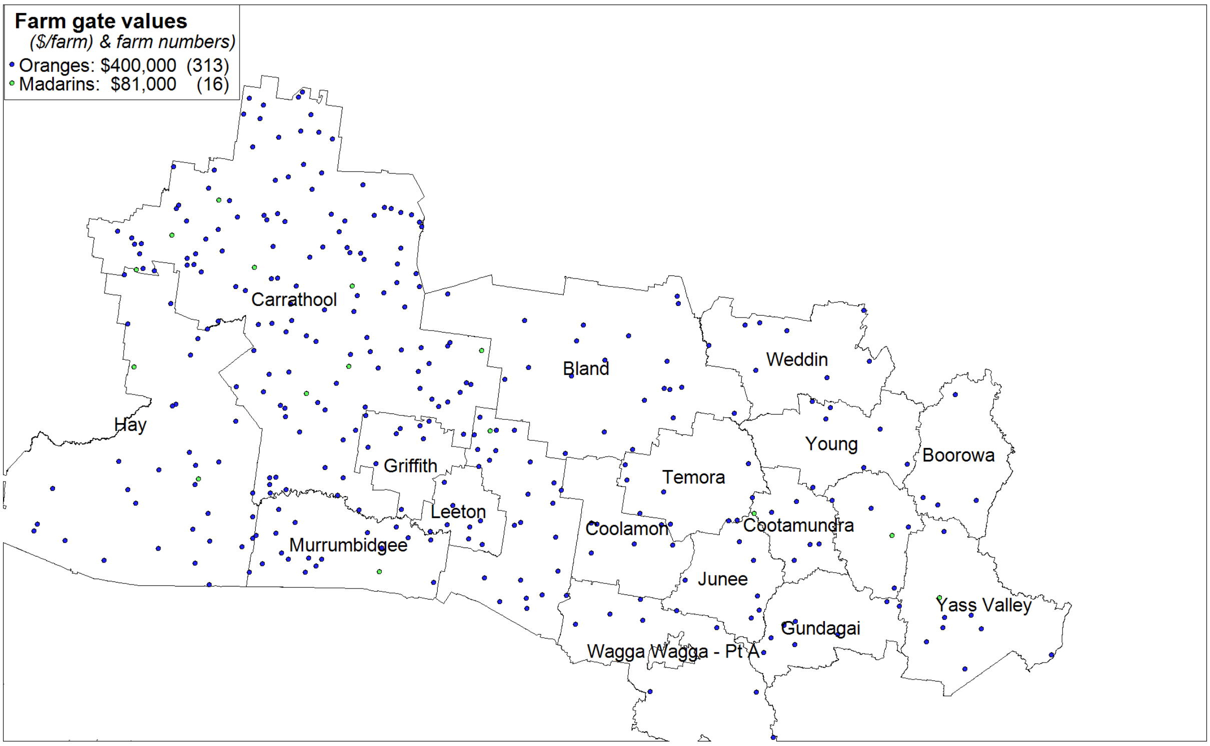


Table 26: Most likely Net Present Value of citrus canker costs in the Riverina region *(A$ thousand)*

Year	Cost contents		Total cost
	Yield loss	Market access loss	
0	10	1	11
1	24	3	26
2	59	7	66
3	148	16	164
4	367	40	408
5	914	101	1,014
6	2,272	250	2,523
7	5,652	623	6,275
8	5,487	605	6,092
9	5,327	587	5,914
10	5,172	570	5,742
11	5,022	553	5,575
12	4,875	537	5,412
13	4,733	521	5,255
14	4,596	506	5,102
15	4,462	492	4,953
Total	49,120	5,411	54,531
Average per year after endemic	5,036	555	5,591

Figure 23: Spread of citrus canker in the Riverina region, year 4

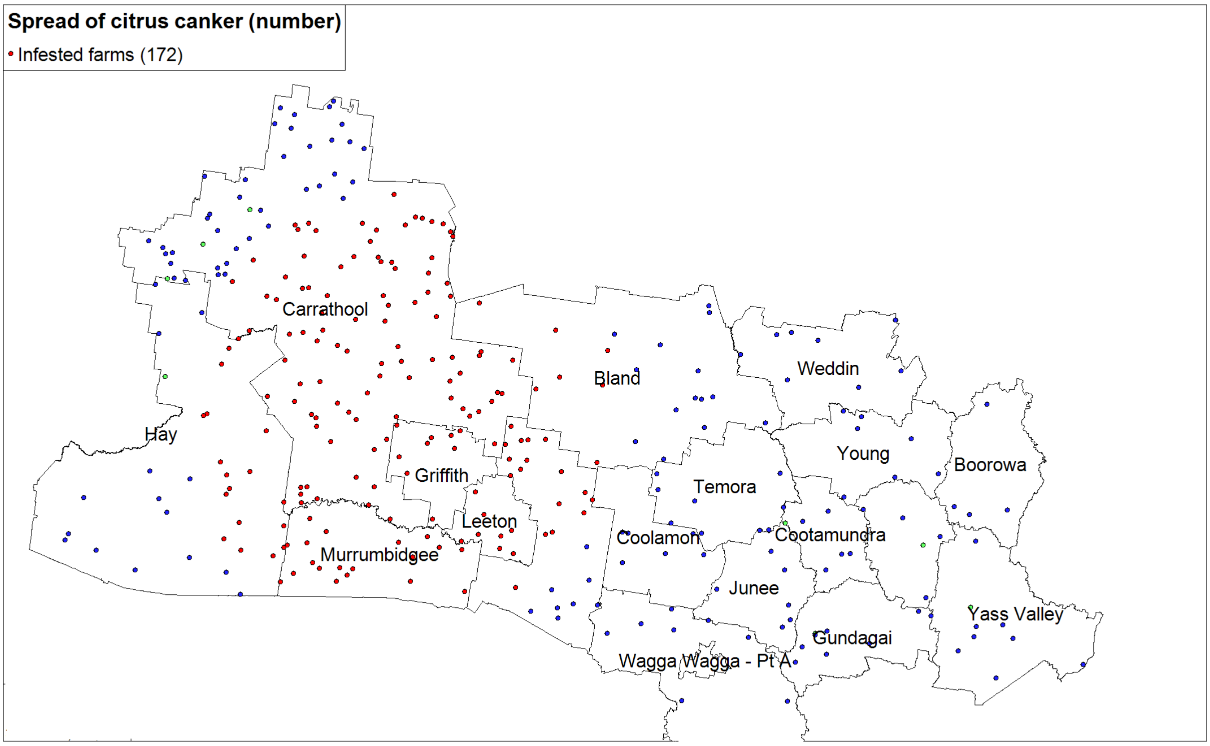
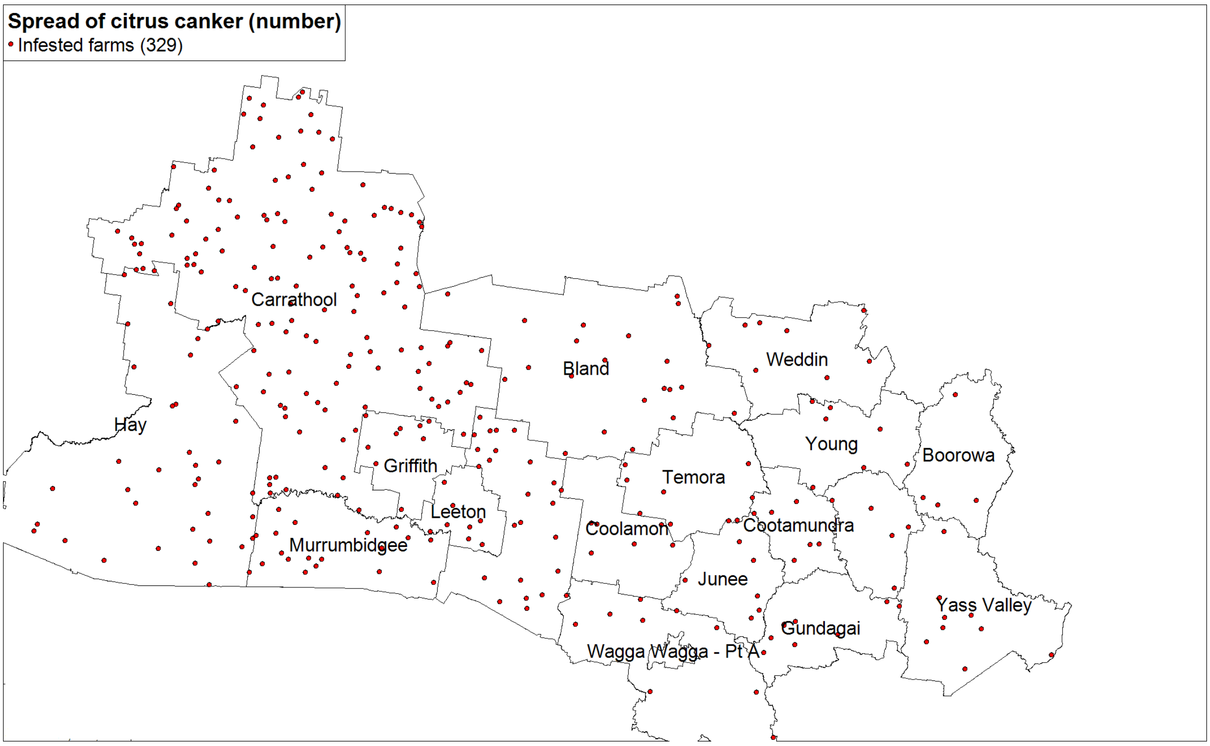


Figure 24: Spread of citrus canker in the Riverina region, year 9



2.7 Closing remarks for Citrus Canker

Australia is currently free of citrus canker. Outbreaks are rare, with the last detection occurring in Emerald, Queensland, in May 2005. Citrus canker would have multiple effects on the Australian citrus industry. The most important effects of a citrus canker outbreak and spread are yield and market access losses. The market access loss generally results from the lower price for fresh fruit sold in premium (export) and domestic markets. Applying a spatial-economic model and using Monte Carlo stimulations, the potential costs of citrus canker in Queensland is estimated. Over the period of 15 years, at a 90 percent likelihood, the potential costs of citrus canker ranged from A\$74 million to A\$89 million for Queensland. On average, the average potential cost of a citrus canker incursion is estimated to be A\$6.9 million per year.

The case studies of the Burnett Mary region (Queensland) and the Riverina (NSW) confirm that a future CC outbreak is likely to impose a large economic cost in these regions. Over the 15 year period considered in this analysis, the potential costs of citrus canker is estimated to be A\$81 million for the Burnett Mary region (Queensland) and about A\$54.5 million for the Riverina (NSW).

3 Rabies

Rabies is caused by infection with viruses of the genus *Lyssavirus*, family *Rhabdoviridae*. The disease is a zoonotic disease (a disease that is transmitted to humans from animals). Human rabies is found wherever animal rabies is found. The disease is virtually always fatal in humans once symptoms appear, and medical advice should be immediately sought if there is a risk of infection (Australian Veterinary Emergency Plan (AUSVETPLAN) 2011). Rabies infections in humans cause a fatal encephalitic disease, which is is estimated to be responsible for more than 55,000 deaths per year in the world (Knobel et.al 2005). The disease is a significant public health issue in Africa and Asia where more than 95 per cent of human deaths from this type of infection occur (World Health Organisation (WHO) 2014).

The rabies virus is spread from infected animals to people through bites or scratches, or by exposing people to an infected animal's saliva through the eyes, nose or mouth. Rabies may also result from licks to broken skin, saliva on mucous membranes and through organ transplantation. Only mammals can be infected, with dogs being the main source of the disease in people. Other animals that transmit rabies include bats, foxes, cats, raccoons, skunks, jackals and mongooses. Monkeys may be able to transmit rabies but the risk is low. Rabies has also been spread through organ transplantation (Department of Health of Australia (DHA) 2014).

Rabies virus occurs throughout most of the world except New Zealand, Papua New Guinea, Japan, Great Britain and Ireland. Recently, there has been an outbreak of rabies in the Indonesian islands of Bali and Flores; previously, these islands had been considered rabies free (AUSVETPLAN 2011). Australia is also rabies free, but the risk of the disease's occurrence and an outbreak is believed to be increasing (Brain 2012).

In developing countries, dogs are the principal reservoir of the rabies virus and are responsible for 99 per cent of human infections (DHA 2014). In Australia, dogs are a common pet, being present in approximately 39 per cent of households (Animal Health Alliance 2014). Given the large number of dogs in Australia, any outbreak and spread of rabies could pose significant risks to human health and associated economic losses. Sources of risk are the potential for rabies to spread to domestically-housed dogs via transmission from infected dogs that illegally enter the country, a problem that recently occurred in Bali.

Along with dogs, the risk of rabies also comes from other sources. As indicated in AUSVETPLAN (2011), Australia has widespread and abundant populations of wildlife and feral animals that are known to be maintenance hosts of rabies in other countries. Carnivore species in Australia that may be potential hosts are the European red fox, the feral cat, the feral dog and the dingo. Although threshold densities needed to maintain rabies vary widely, even within the same species (for example the red fox in Canada and Europe), it is known that Australia has densities of the European red fox that greatly exceed the densities of rabies in infected populations within endemic countries.

The risk of rabies from wildlife and feral animals is potentially large, but it is difficult to predict which wildlife species would be involved in an outbreak in Australia (AUSVETPLAN 2011). Given that constraint, this report focuses on the estimation of the potential cost of mass vaccinations of dogs for controlling a rabies outbreak, the costs of medical treatment and livestock losses for the case in which rabies becomes endemic. Estimation of the potential costs of a rabies endemic to Australia provides a measure of the benefits in terms of the avoided losses that go with preventing entry.

The next section provides some background information, including the impact of rabies worldwide and the increasing risk of rabies in Australia. The sections that follow provide a brief on the management strategy used for a potential rabies outbreak in Australia, a simple economic analysis and estimated losses of rabies in Australia.

3.1 Background of rabies effects and risks to Australia

3.1.1 Effect of rabies on human health in the world

Rabies is estimated to be responsible for more than 31,500 and 23,700 deaths per year in Asia and Africa, respectively. Most of rabies deaths are in the rural areas of Asia and Africa, with the highest incidence in children under 15 years (Knobel et. al 2005). Tables 27 and 28 summarise the human health impacts of rabies resulting from transmission by dogs, which is the primary transmission form in Asia and Africa (Knobel et al., 2005).

Control of rabies in animal reservoirs, particularly domestic dogs, is argued to be the only means of eradicating the disease (Coleman and Dye, 1996; Zinsstag et al. 2009). Eradication provides substantial economic benefits, with the economic costs of rabies in Africa and Asia alone being estimated at more than US$700 million (Knobel et al. 2014).

3.1.2 Increasing risks of rabies in Australia

Australia is rabies free. However, there was one probable occurrence in Tasmania in 1867 that involved several dogs, a pig and a child bitten by one of the dogs. In two more recent cases (1987 and 1990), individual children, who contracted the infection in endemic countries, developed the clinical disease in Australia after a protracted incubation (AUSVETPLAN 2011).

According to Brain (2012), the risk of rabies reaching northern Australia is increasing. More than 150 people have died of rabies in Bali since the illness arrived there from a rabid dog on a fishing boat four years ago. According to Brain (2014), at least 23,000 people travel between Papua New Guinea, the Torres Strait Islands and Cape York Peninsula every year, some of whom are accompanied by dogs despite quarantine restrictions. Another disease transmission pathway is yacht travel or fishing vessel movements between Indonesia and Australia, both of which are difficult to control. According to Ward (2012) and Ward and Durr (2012), during the past 10–15 years rabies has spread to areas of eastern Indonesia that previously were rabies-free, such as Flores and Bali.

An ACIAR project conducted by the University of Sydney (Ward 2012), provides an improved understanding of how rabies might spread to Australia from Indonesia, and the risks of

Table 27: Estimated human mortality caused by rabies in Africa and Asia

Contents	Asia			Africa
	India	China	Other Asia	
No. subregional deaths	19,713	2,336	9,489	
	(4192–39733)	*(2281–19503)*		
	All Asia			
No. regional deaths	31.529			23,705
	(8,149–61,425)			*(23,910–93,057)*
	Asia and Africa			
Total no. deaths	55,270			
	(23,910–93,057)			
No. deaths /100,000 pers	1.38			
	(0.60–2.33)			
Predicted death in the absence of any post-exposure treatment	327,160			
	(16,6904–525,427)			

Source: Knobel et.al (2005) Note: Rabies death are the means of the probability distributions calculated independently and may therefore not sum exactly. Figures in parentheses are the 5th and 95th percentile of the probability distribution.

Table 28: Estimated annual costs of rabies in Africa and Asia *(U$ million)*

Category	Africa	Asia
Medical costs	9.1	475.9
	(8.2–10.0)	*(435.0–520.5)*
Dog rabies control costs	9.7	77.0
	(8.8–10.6)	*(71.5–82.3)*

Source: Knobel et.al (2005). Note: Values are at 2015 prices; Figures in parentheses are the 5th and 95th percentile of the probability distribution.

spread via different pathways. The report includes information on the frequency with which dogs are transported between islands based on information, including direct observations, on ferries and fishing boats. The size of dog populations in rabies-free areas was found to have a significant influence on the risk of rabies spread (Ward and Durr 2012; Ward 2014). The ACIAR-funded study also identified options for mitigating the risks of rabies spread, including alternative surveillance systems to detect potential incursions in the northern Australia and the Torres Strait. One of the findings of this research (see University of Sydney, Ward 2012), was that the risk of rabies reaching northern Australia is increasing as the virus, which normally is transmitted by dogs, is spreading through Indonesia. In 2010, the disease reached the Tanimbar Islands, part of the Moluccas, just 350 kilometres north of the 'Top End' of Australia. If rabies reaches Papua New Guinea, it may be difficult to prevent its spread into Australia.

3.2 Management strategy of a rabies outbreak in Australia

In consultation with Australian national, state and territorial governments and industry, the Australian Veterinary Emergency Plan (AUSVETPLAN) (2011) sets out a manual or management strategy in the event of a rabies outbreak in Australia. This strategy contains relevant risk factors and treatment protocols, the options for the management of a disease outbreak, and the policy that will be adopted in the case of an outbreak in Australia.

Rabies is included on the World Organisation for Animal Health (OIE) list of notifiable diseases.[1] This obliges OIE member countries that had been free from the disease to notify the OIE within 24 hours of confirming the presence of rabies. The AUSVETPLAN strategies for the diagnosis and management of an outbreak of rabies are based on the recommendations in the OIE *Terrestrial Animal Health Code* and the OIE *Manual of Diagnostic Tests and Vaccines for Terrestrial Animals* (AUSVETPLAN 2011).

3.2.1 Principles of control and eradication of rabies

AUSVETPLAN principles of control and eradication of rabies in Australia include critical factors assessed in formulating response strategy and options for control and eradication.

Critical factors assessed in formulating a response strategy. According to AUSVETPLAN (2011), vaccination is an effective technique for controlling rabies in Australia. Availability of vaccine for humans and animals is essential, which requires safe and effective registered parenteral vaccines for humans and animals. Oral vaccination programs in some species have effectively eradicated or controlled rabies in wildlife overseas. It is suggested that more than 70 per cent of the population needs to be vaccinated. The use of oral vaccine in wild animal management has been considered as an option in Australia. However, safety and efficacy would need to be evaluated, and an emergency-use permit would need to be obtained (AUSVETPLAN 2011).

Options for control and eradication of rabies in Australia. Options for the control and eradication of rabies in Australia will apply for infected animals; confirmed cases; susceptible animals, suspect animals, dangerous contact animals and trace animals. Following AUSVETPLAN (2011), rabies control measures could involve any or all of the following:

- Recognising rabies cases in animals as early as possible; defining the geographic area of the outbreak; seizing, and quarantining or destroying infected animals; tracing, seizing, and quarantining or destroying dangerous contact animals.
- Controlling zoning and movement over animals, including prohibiting gatherings, sporting and recreational activities involving animals (e.g., an embargo on hunting dogs, and mustering that uses working dogs).
- Muzzling all domestic dogs when in public to minimise the risk of transmission.
- Vaccinating key populations (e.g., guide dogs, police dogs) early in the response.
- Alerting all veterinary practices such as state and territory health departments, wildlife carers, animal shelters, and local government animal control organisations.
- Controlling stray animals; and seizing, detaining or destroying animals not properly controlled or vaccinated.

[1] OIE-listed diseases are diseases with the potential for international spread, significant mortality or morbidity within the susceptible species, and/or potential for zoonotic spread to humans.

- Vaccinating individual animals using oral vaccinations (e.g., through baiting) for large populations; identifying vaccinated animals.

- Detecting and managing the disease in wildlife; mounting publicity campaigns; reporting human exposure to possibly infected animals; and identifying and assessing trace animals.

3.2.2 Strategy for the control and eradication of rabies

For the case of detected rabies, the AUSVETPLAN policy is to quickly eradicate rabies to prevent spread to domestic and wild animals, and humans, through a combination of strategies including:

- Quarantine and movement controls on susceptible animals in declared areas to minimise the spread of infection.

- Destruction of infected animals to remove the most dangerous sources of the virus.

- Quarantine, vaccination or destruction of exposed animals.

- Movement controls, vaccination or quarantine of suspect animals until their rabies status has been clarified.

- Vaccination of domesticated carnivores (e.g., dogs, cats, ferrets), other selected species and targeted animal groups in declared areas to protect animals against infection and reduce exposure of humans.

- Monitoring of wild animals and, if the disease establishes in those populations, possibly implementing a vaccination program.

- Tracing and surveillance to determine the source and extent of infection, and to provide proof of freedom from the disease.

- Linkage and coordination of public health and environmental authorities so that they are co-responders.

- A public awareness campaign to facilitate public cooperation from animal owners and the community, including other government and non-governmental authorities.

3.2.3 Recommended quarantine and movement controls

The AUSVETPLAN strategy of rabies control and eradication in Australia also provides guidelines for classifying declared areas and premises. Infected premises are defined by: infected premises; dangerous contact premises; suspect premises; and trace premises.

Declared areas are defined for restricted areas; transmission area and control areas. A restricted area (RA) includes home ranges of wildlife or feral animals. Under the protocol, the RA will be subject to intense surveillance and movement controls. Movement of susceptible animals out of the area will, in general, be prohibited, while movement into the area only by permit. Multiple RAs may exist within one control area (CA). The size of the RA will depend on the ecology of the maintenance host(s). The boundary will take into account the distribution and density of susceptible animals.

The transmission area (TA) is a declared area option that could be implemented by the affected jurisdiction's chief veterinary officer. It is an area within the declared RA where there may be a need to implement specific control measures. The TA would not need to be circular but could have an irregular perimeter. The CA is a buffer zone between the RA and the non-infected area. The CA will be a larger declared area around the RA(s). The CA is subject to lesser surveillance than the RA. Movement controls may be less restrictive, and animals in the CA may be subject to a vaccination program. Initially, it may be the entire state or territory, to limit the risk of disease spreading from the RA(s). The boundary of the CA will be adjusted as confidence about the extent of the outbreak increases (AUSVETPLAN 2011).

3.3 A basic economic analysis of the potential costs of rabies

Dogs are the principal reservoir of rabies virus and, currently, there is no risk assessment of a rabies threat from wildlife and feral animals. Therefore, this report focuses on estimating the potential costs of rabies entering Australia via the transport of rabid dogs. There are a number of major studies of rabies costs caused by rabid dogs worldwide. In a study by Knobel et al. (2005), the economic impact of rabies in Asia and Africa was estimated, including the direct and indirect cost of Post Exposure Treatment (PET) of human-dog attack victims. Other costs estimated include the cost of rabies control in dog populations, disease surveillance costs and costs arising from livestock losses (Knobel et al. 2005). Bogel and Meslin (1990) developed guidelines for rabies control programs and compared the cost of intensified human PET versus mass dog vaccination. Another study by Fishbein et al. (1991), estimated the benefits and costs of eliminating animal and human rabies in the Philippines. The study by Zinsstag et al. (2009), compared the cost-effectiveness of mass dog vaccination to PET in humans in Chad, Africa, finding that it is more cost effective to combine dog vaccination campaigns with human PET than to rely solely on human PEP over a time-frame of seven years. The cost of rabies PET in humans has also been estimated by other authors (e.g., Bogel and Meslin 1990; Wilde et al. 1999). We draw on these results for estimating the potential costs of rabies in Australia.

3.3.1 Dog populations and dog attacks in Australia

As indicated, according to the Animal Health Alliance (2014), dogs are the most commonly owned pet in Australia, with 39 per cent of households owning a dog. Following Knobel et al. (2005), we estimate dog population densities from data on human populations in urban and rural areas. Since detailed statistics for dogs and dog attacks in Australia is limited, the key parameters used in this report are based on a report by the Department of Premier and Cabinet of NSW (2013), with an assumed comparability for Queensland. There are an estimated 4.2 million pet dogs in Australia with an ownership rate of 19 dogs for every 100 people. Table 29, for example, represents data on dog numbers in NSW in 2011–12. The average ratio of humans to dogs in NSW is about 22.5 per 100 people. Table 30 provides the estimated populations of dogs in Australia, taking into account uncertainty about dog density in Australia.

Dog attacks are not uncommon in Australia. For example, the number of dog attacks in 2011–12 in NSW was 5,650 (see Table 31), a 10 per cent increase compared with 2010–11 (Department of Premier and Cabinet of NSW, 2013). Since more than one dog can be involved in a single attack, the total number of dogs involved in attacks is probably higher than the number of attacks. The average number of dogs involved in an attack in 2011–12 was 1.3. Since there may be more than one victim in a single attack, the number of victims, both human and animal, is also higher than the number of attacks (Department of Premier and Cabinet of NSW 2013). On average, there was one human victim for every 1.7 attacks. Based on data provided by the Department of Premier and Cabinet of NSW (2013), the risk of dog attacks to people and animals appears to be increasing. Since 2011–12, the number of reported human victims of dog attacks has increased by 10 per cent and the number of reported animal victims has increased by 13 per cent.

Table 29: Statistics for dogs in New South Wales in 2011–12

Age of dog	Number	Percentage
Less than 6 months old	18,719	1%
6 months to $\leqq$ 12 months old	51,644	3%
1 year to $\leqq$ 2 years old	112,532	7%
2 years to $\leqq$ 5 years old	357,104	21%
5 years to $\leqq$ 10 years old	549,848	33%
10 years old and over	595,808	35%
Total	1,685,655	100%

Source: Department of Premier and Cabinet of NSW, 2013.

Table 30: Estimated dog population in Australia by state (*numbers*)

State	Minimum	Most likely	Maximum
Queensland	410,000	841,400	1,628,900
New South Wales	1,431,700	1,686,600	1,927,200
Victoria	88,400	1,040,400	2,171,900
South Australia	173,000	300,700	604,700

Source: Authors calculations.

Table 31: Statistics for dog attacks in New South Wales in 2011–12

Total attacks reported	Dogs involved in an attack	Human victims	Animal victims
5,650	7,381	3,323	5,340

Source: Department of Premier and Cabinet of NSW, 2013.

3.3.2 Economic analysis of the potential costs of rabies

In this study, a simple spatial economic approach is applied to estimate the potential costs of rabies in Australia. Based on population distributions by region in Australia, dog populations are estimated. Dog density varies significantly with the density of the human population. Therefore, the potential cost of rabies varies by location and dog density. Unfortunately, we have no information on the potential spread and relative density-spread of rabies and thus no opportunity to fit a model like that used for PFF or CC.

Therefore, this part of the report focuses simply on estimating potential costs of rabies for the two basic cases. Case 1 is for the AUSVETPLAN (2011) control and eradication option, used as soon as possible once rabies is detected. In this case, the cost of dog vaccinations, which is the most important cost of rabies management, is estimated. Case 2 is for rabies as endemic, or without the eradication of a rabies outbreak. The cost of rabies when endemic calibrates the potential benefit that the eradication option of rabies delivers for Australia. The cost of rabies as endemic includes Post Expose Treatment (PET) costs, other treatment costs and livestock losses. Given our purpose, the 'spatial factor' of the cost of rabies in this report simply refers to where there is either a rabies outbreak or where it is endemic. A GIS application is used to map dog distributions in Australia, where dog density varies by location and, as such, will greatly influence the potential costs of rabies.[2]

Case 1: Eradication of rabies outbreak.
For control and eradication of a rabies outbreak, all dogs in Control Area (CA) may be subject to vaccination. Other costs are also required, including animal health and human health services, surveillance, movement controls, wild animal controls and so on (AUSVETPLAN 2011). However, most of these costs are not available or can be estimated for Australia. Therefore, this report focus on estimating mass dog vaccination costs in the control area, which is the major cost of rabies control and eradication in any case.

The potential economic cost of dog vaccination at time (t) and space j (or $C(d)_{t,j}$) is given by:

$$C(d)_{t,j} = a_{t,j} \rho N(v)_{t,j} \tag{22}$$

where $a_{t,j}$ includes the direct and private costs of dog vaccinations; ρ is the rate of dog population vaccinated; and $N(v)_{t,j}$ is the dog population in the control area.

Exact data and guidance for the calculation of dog populations in the control area, however, is unavailable. We approximate in this report by assuming that the dog population in the control area $(N(v)_{t,j})$ is computed from the total dog population in the outbreak area, the size of outbreak area and size of control area, given by:

$$N(v)_{t,j} = N_{t,j} \frac{S_{t,j}}{S(v)_t, j)} \tag{23}$$

where $N_{t,j}$ is the dog population in the outbreak area (such as Brisbane or Sydney); $S_{t,j}$ is the size of outbreak area; and $S(v)_{t,j}$ is the size of control area.

The maximum cost of dog vaccinations would occur if a rabies outbreak occurred in areas with the highest dog-density. Therefore, the maximum vaccination cost is estimated based on

[2]Bogel and Meslin (1990), examining practice in India and other cases using a combination of Post Exposure Treatment (PET), preventative measures and dog vaccinations, found that this combined option was more cost effective than mass dog vaccinations or PET alone. Given Australia's AUSVETPLAN strategy for control and eradication of rabies, however, along with a lack of needed parameters and risk assessments, the case examined by Bogel and Meslin (1990) is not included in this report.

an assumption that a rabies outbreak occurred in Brisbane (for Queensland), Sydney (for New South Wales), Melbourne (for Victoria) and Adelaide (for South of Australia).

Case 2: Rabies endemic.
Without an eradication option for a rabies outbreak, rabies will become endemic and will cost Australia 'Post Expose Treatment' (PET) treatments and livestock losses yearly. Following Knobel et al. (2005), it is assumed that PET treatment, when applied at an early stage, using the rabies vaccine in combination with rabies immunoglobulin, is 100 per cent effective in preventing death. The approach taken here to estimate the probability of dog bites is based on that of Cleaveland et al. (2002). Not all bites from rabid dogs result in infection and not every infection leads to clinical signs and death. One of the principal factors influencing the outcome of a bite by rabid dogs is the location of injuries on the body (Baltazard and Ghodssi 1954; Shah and Jaswal (1976). Based on distribution of injuries on the body and the likelihood of successful treatment, the probability of different consequences of bites from rabid dogs can be estimated (see Cleaveland et al. 2002; 2003). Applying a basic risk analysis (see Vose 2000), our model analyses the incidence of bites from suspected rabid dogs that potentially could result in human deaths.

Knobel et al. (2005) estimated the human population at risk from canine rabies as the number of people living in areas affected by canine rabies, where the density of the dog population exceeds a specific threshold. The threshold density is the level at which canine rabies is capable of being maintained endemically. This threshold for rabies persistence was estimated by Knobel et al. (2005) at 4.5 dogs per km^2, based on predictions made with data on rabies transmission in Africa.

The potential economic cost of PET treatments at time (t) and in space j is given by

$$C(PET)_{t,j} = b_{t+1,j}P_{t,j} \tag{24}$$

where $b_{t,j}$ includes the direct and private costs of PET treatments. In Equation (24), $P_{t,j}$ is the number of PET patients at time $t+1$ in space j, given by

$$P_{t,j} = f(N_{t,j}, Y_j)p_1p_2p_3 \tag{25}$$

where f is the rabid dog attack function, which depends on a number of rabid dogs (N) and human population size (Y) at time t in land unit j; p_1 is the probability of human attack by rabid dogs over the total dog population; p_2 is the probability of dog bites resulting in infection; and p_3 is the probability of infection leading to clinical signs.

For calibrating the economic model we use Monte Carlo stimulations throughout. In this report, dog population distribution, in a spatial group of 200, is characterised using a basic GIS application.

The potential economic cost of livestock loss at time (t) in space j is given by

$$C(L)_{t,j} = \chi L_{t,j}V(L)_{t,j} \tag{26}$$

where χ is the rabies rate of incidence; and $L_{t,j}$ and $V(L)_{t,j}$ is number of cattle and average value per cattle at time (t) in space j.

3.4 Estimates of the potential cost of rabid dogs in Australia

3.4.1 Key assumptions and parameters

Due to a lack of data, the costs of surveillance for rabies management are not considered here, with a focus instead on the direct costs of PET treatments and dog vaccinations. These direct costs include the lost time for rabies patients in undertaking vaccination or other treatments for themselves or their dogs.

To estimate the costs of dog vaccinations, it is assumed that following the initial rabies vaccination, a booster vaccination is applied within one year. Once this second rabies vaccine has been administered, dogs should receive rabies vaccines every three years unless regulations in the community demand otherwise. Since expected dog lifetime varies by different breeds, a distribution is assumed for the number of dog vaccinations per year in expected lifetimes. The rate of dog populations vaccinated is taken as 0.7 (AUSVETPLAN 2011). Other key cost parameters for dog vaccinations per visit are given in Table 32.

Some costs are not included due to a lack of information. For example, the cost of a veterinarian administering a vaccination is not available, but it should be added to costs in principle. A parameter for dog vaccination by the Animal Service Agency (2014) is assumed and dogs are taken as vaccinated in a clinic with transport costs and the time opportunity costs of dog owners accounted for. Population data are taken from the ABS (2014c). It is important to note that it may be more cost effective if a relevant combination of preventive measures and dog vaccinations is applied.

For Australia, the size of control area is also not available. Therefore, in this report, the size of control area is estimated based on an assumption that rabies spread and control occurs within several months, with a control area in place for up to a year in length. Based on AUSVETPLAN (2011), rabies epidemics often spread on a slow-moving front; for example, a 30–60 kilometre per year spread in fox rabies in Europe (Toma and Andral 1977). Therefore, it is assumed the maximum control area could be up to a area with a radius of 30 kilometres from the initial outbreak (or 2826 km^2 equivalent).

The parameters for estimating the potential number of PET patients are based on Knobel et al. (2005), including the parameters of bites from suspected dogs over the population at risk (see Table 33). For Australia, rabies death is not assumed. Following Knobel et al. (2005), the time opportunity costs are estimated on the basis of average GDP per capita and the average time lost by patients and those accompanying them in treatment. Transport cost is based on the cost of gasoline and the average distance travelled to clinics. Table 34 presents medical costs of Post Exposure Treatment (PET) in Australia, which is derived from Knobel et al. (2005), the Reserve Bank of Australia (2015) and the US Department of Labour (2015). The costs in terms of the potential loss to livestock from a rabies infection and associated agricultural values is also included. Based on Knobel et al. (2005), the rabies rate of incidence per 100,000 livestock is 5. Statistics for livestock in Australia are presented in Table 35.

Table 32: Dog vaccination costs per visit

Contents	Cost *($)*
Dog vaccination	$6.0
Private costs: transport cost	$25.0
Time opportunity loss for animal owner (0.5 day)	$58.6
Cost per visit	$89.6

Sources: Drawn from the Animal Services Agency (2014); Knobel et al. (2005), Department of Labour of the United States (DOL) (2015), RBA (Reserve Bank of Australia) (2015), Australian Bureau Statistics (2014d).

Table 33: Estimated human mortality caused by rabies in Africa and Asia

Estimated results	Asia						Africa	
	India		China		Other Asia			
	Urban	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*
Population at risk (millions)	284.7	710.4	459.1	498.3	295.7	409.1	294.2	340.1
No bites from suspected	409.4	893.4	660.1	626.7	425.2	514.5	374.3	427.8
rabid dogs (thous)								
No. of rabies deaths	1,058	1,821	1,324	1,257	853	8,135	5,886	17,937
No. death/100,000	0.37	2.49	0.29	0.15	0.29	1.55	2.00	3.60

Source: Knobel et.al (2005).

Table 34: Medical costs of Post Exposure Treatment (PET) in Australia *(2015 prices)*

Contents	Cost details
Common costs	
Material costs per injection (includes needles, syriges , swabs,ect.)	$0.13
Overhead costs per PET visit	$30
Tissue-culture vaccines costs	
Inframuscular vaccination	
Vaccine cost per dose	$13.35
Visit per patient	3
Injection per patient	3
Intrademal vaccination	
Vaccine cost per dose	$3.34
Visits per patient	3
Injection per patient	6
Nerve–tissue vaccine costs	
Vaccine cost per dose	$0.53
Visits per patient	7
Injection per patient	7
Rabies immunoglobullin	
Human rabies immunoglobullin cost per dose	A$146.80
Equine rabies immunoglobullin cost per dose	A$33.36

Source: Derived from Knobel et al. (2005); the US Department of Labour (DOL) (2015) and the Reserve Bank of Australia (2015).

Table 35: Cattle and average cattle value by state, 2013

Contents	NSW	VIC	QLD	SA
Cattle numbers (*no*)	5,953,222	4,228,971	12,798,010	1,326,844
Values slaughtered (*A$mil*)	1483.52	1,165.89	3410.56	334.60
Milk and wools (*A$mil*)	1270.11	2834.74	399.98	567.02
Value per head ($/*head*)	462.5	946.0	297.7	679.5

Source: Australian Bureau Statistics, 2014a,b.

3.4.2 Estimated results for rabid dogs in Queensland

We combine all of our information and assumptions and simulate a basic outbreak and spread of rabies in Queensland. It is assumed that the outbreak spreads from north to south. Table 36 presents the estimated potential costs of rabies in Queensland. If a rabies outbreak occurred in Brisbane (the highest dog-density area in Queensland), the potential maximum costs of dog vaccinations is estimated to be \$5.9 million. If rabies becomes endemic, the potential costs of PET could be up to \$3.8 million per year. Livestock losses are estimated to be \$191,000 per year.

Table 36: Potential costs of rabies in Queensland *(mean values)*

Contents	Unit	Urban	Rural	Total
Case 1. Eradication of rabies outbreak				
Mass dogs vaccinated	*thous*			66.5
Vaccination costs	\$*thous*			5,900
Case 2. Rabies endemic (without eradication) (cost/year)				
	Post Exposure Treatment cost/year			
Direct costs				
PET treatments	\$*thous*	1,118	1,234	2,351
Indirect costs				
Average time opportunity loss		0.5	0.5	0.5
Income loss	\$*thous*	519	572	1,091
Transport costs	\$*thous*	158	174	332
Total PET costs	\$*thous*	1,794	1,980	3,775
	Livestock losses/year			
Livestock losses	\$*thous*		191	191

3.4.3 Estimated results for rabid dogs in New South Wales

We next simulate a basic outbreak and spread of rabies in NSW. It is assumed that the outbreak of rabies would begin in the north and spread in the south-east direction. Table 37 presents the estimated potential costs of rabies in NSW. If a rabies outbreak occurred in Sydney (the highest dog-density area in New South Wales). The potential maximum costs of dog vaccinations is estimated at \$8.5 million. If rabies becomes endemic, the potential costs of PET could be up to \$6.0 million per year. Livestock losses are about \$138,000 per year.

3.4.4 Estimation results of potential cos of rabid dogs in Victoria

To simulate a basic outbreak and spread of rabies in in Victoria, we assume that the outbreak would spread from the north to the south of the state. The estimated potential costs of rabies in Victoria is presented in Table 38. If a rabies outbreak occurred in Melbourne (the highest

Table 37: Potential costs of rabies in New South Wales *(mean values)*

Contents	Unit	Urban	Rural	Total
Case 1. Eradication of rabies outbreak				
Average dogs vaccinated	*thous*			95.5
Vaccination costs	$*thous*			8,500
Case 2. Rabies endemic (without eradication) (cost/year)				
	Post Exposure Treatment cost/year			
Direct costs				
PET treatments	$*thous*	2,606	1,140	3,476
Indirect costs				
Average time opportunity loss		0.5	0.5	0.5
Income loss	$*thous*	1,209	529	1,738
Transport costs	$*thous*	368	161	529
Total PET costs	$*thous*	4,183	1,830	6,013
	Livestock loss/year			
Livestock losses	$*thous*		138	138

dog-density area in Victoria), the potential maximum costs of dog vaccinations is estimated at \$7.7 million. If rabies becomes endemic, the potential costs of PET could be up to \$4.7 million per year. Livestock losses are about \$200,000 per year.

Table 38: Potential costs of rabies in Victoria *(mean values)*

Contents	Unit	Urban	Rural	Total
Case 1. Eradication of rabies outbreak				
Average dogs vaccinated	*thous*			85.4
Vaccination costs	\$*thous*			7,700
Case 2. Rabies endemic (without eradication) (cost/year)				
	Post Exposure Treatment cost/year			
Direct costs				
PET treatments	\$*thous*	2,411	497	2,907
Indirect costs				
Average time opportunity loss		0.5	0.5	0.5
Income loss	\$*thous*	1,119	230	1,349
Transport costs	\$*thous*	341	70	411
Total PET costs	\$*thous*	3,871	797	4,667
	Livestock loss/year			
Livestock losses	\$*thous*		200	200

3.4.5 Estimation results of potential costs of rabid dogs in South Australia

Fianlly, we simulate an outbreak of rabies in South Australia. It is assumed that the outbreak of rabies would spread from north to south and east to west of the state. Table 39 presents the estimated results of the potential costs of rabies in South Australia. If rabies outbreak occurred in Adelaide (the highest dog-density area in South Australia), the potential maximum costs of dog vaccinations is estimated at \$5.8 million. If rabies becomes endemic, the potential costs of PET per year could be up to \$1.3 million per year. Livestock losses are about \$45,000 per year.

3.5 Closing remarks for Rabies

The risk of rabies from illegal movements of infected dogs on fishing boats is believed to be substantial. Rabies was thought to have been introduced into Bali in 2007 via the illegal movement of infected dogs on fishing boats. Given the movement of fishing and other vessels around eastern Indonesia, East Timor, Papua New Guinea and northern Australia, rabies will likely continue to spread in this region, increasing the risk that it will enter Australia (Ward 2012).

According to DHA (2014), dogs are the principal reservoir of the rabies virus in regions where there are substantial human mortality from the disease. For the control a rabies outbreak in

Table 39: Potential costs of rabies in South Australia *(mean values)*

Contents	Unit	Urban	Rural	Total
Case 1. Eradication of rabies outbreak				
Average dogs vaccinated	*thous*			65.1
Vaccination costs	$*thous*			5,800
Case 2. Rabies endemic (without eradication) (cost/year)				
	Post Exposure Treatment cost/year			
Direct costs				
PET treatments	$*thous*	520	321	840
Indirect costs				
Average time opportunity loss		0.5	0.5	0.5
Income loss	$*thous*	241	149	390
Transport costs	$*thous*	73	45	119
Total PET costs	$*thous*	834	515	1,349
	Livestock loss/year			
Livestock losses	$*thous*		45	45

Australia, the maximum cost of dog vaccinations is estimated to be $5.9 million, $8.5 million, $7.7 million and $5.8 for Queensland, NSW, Victoria and South Australia, respectively. For the case of rabies as endemic, the average cost of PET treatments per year are estimated to be $3.8 million, $6.0 million, $4.7 million and $1.3 for Queensland, NSW, Victoria and South Australia, respectively. Losses to livestock range from $45,000 to $200,000 per year, by state.

Summary Remarks for the Overall Report

Australia is relatively free of major exotic pests and diseases The role of preventive biosecurity measures in Australia is vital to Australia's competitiveness in international markets. This report provides baseline consequence measures for three case studies, papaya fruit fly, citrus canker and rabies. The baseline measures can help inform cost-benefit analysis, portfolio allocation models and other modelling techniques, such as Bayesian networks. In summary we found the following:

- Papaya fruit fly is a serious pest worldwide, which is native to and widespread in South-East Asia and present in Papua New Guinea since 1992. In Australia, PFF was detected near Cairns in October 1995 and was successfully eradicated. The major horticultural areas, which are under potential threat of PFF, are the Wet Tropic region, the Burnett Mary region, the Burdekin region, the Border Rivers Naranoa–Balonne, the South west, the Fitzroy and the Northern region. There were about 2000 potential host PFF farms located in QLD in 2013. Estimated results in this report indicate the average nominal cost per year in Queensland caused by a PFF endemic is $16.1 million. The total net present value of the PFF potential cost (over 25 years) is estimated to be from $214.3 million to $250.0 million with an average of $231.9 million. The PFF cost is the most significant for the Wet Tropic areas ($ 6.7 million dollars per year), following by Burnett Mary ($4.3 million per year) and Border Rivers Naranoa-Balone ($2.2 million per year). The potential cost of PFF to the banana industry, alone, is the most significant at about $88 million over a total of 25 years, or 38 per cent of the state's total cost. In terms of optimal local surveillance, it appears that the current surveillance grid used for early detection in QLD is too large, with insufficient resources directed at this activity.

- The outbreak and spread of citrus canker could have multiple effects on the Australian citrus industry, including yield loss and market access loss. The endemic cost of citrus canker in Queensland is considerable. The estimated results indicate that over the period of 15 years, at a 90 percent confidence interval, the potential costs of citrus canker range from $74 million to $89 million. On average, the annual potential cost of a citrus canker endemic is estimated to be $7.1 million for Queensland.

- Rabies is a zoonosis caused by the rabies virus of the genus Lyssavirus *(Rhabdoviridae family)*. The disease is one of the most serious public health diseases in the world, resulting in more than 50,000 deaths per year. For the case of dogs exposed to a rabies virus, the maximum cost of dog vaccinations is estimated to be $5.9 million, $8.5 million, $7.7 million and $5.8 for Queensland, NSW, Victoria and South Australia, respectively. For the case of rabies endemic, the average cost of PET treatments per year are estimated to be $3.8 million, $6.0 million, $4.7 million and $1.3 for Queensland, NSW, Victoria and South Australia, respectively. Losses to livestock ranges from $45,000 to $200,000 per year for each Australian state.

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