



A Practical Optimal Surveillance Measure: The Case of Papaya Fruit Fly in Australia

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Abstract

Surveillance programs have provided an essential protection by identifying the presence of exotic invasive species, thus protecting both consumers and producers from major health concerns and organisms that can potentially destroy local agricultural production. The key objective of surveillance activities is 'early detection'. However, surveillance activities can be costly depending on the severity of the surveillance measures in place and how 'early' detection is targeted to occur given a potential incursion. This paper develops a practical model to determine an optimal plant surveillance measure against exotic invasive specie. The object is to minimize the sum of the direct costs of a pest or disease incursion before detection and during the management period, the cost of the management program given the detection of a pest or disease and the cost of the surveillance activity itself through a choice of the area and density of infestation, and thus the time length before first detection.

The case of surveillance of Papaya Fruit Fly (PPF) in Australia is discussed as an illustrative example. The content of analysis of PPF is based on the early analysis by Kompas and Che (2003). The further stochastic model of PPF analysis was developed by Kompas et al (2006). PPF is recognised as a serious threat to horticultural crops. An outbreak of PPF in Queensland in 1995 resulted in roughly \$43 million Australian dollars of eradication costs over the period 1995 to 1997. Estimates of an optimal surveillance activity are used to determine whether the current level of surveillance is appropriate to the case of PPF in Australia.

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1. Introduction

The development of trade between regions and countries is an increasingly important characteristic of modern agriculture. In this regard, plant surveillance programs have provided an essential protection by identifying the presence of exotic pests and diseases, thus protecting both consumers and producers from major health concerns and organisms that can potentially destroy local agricultural production. The key objective of plant surveillance activities is 'early detection', or becoming aware of the presence of an exotic pest before damages and management costs become too severe.

However, plant surveillance activities can be costly depending on the severity of the surveillance measures in place and how 'early' detection is targeted to occur given a potential incursion. It is not hard to imagine that vast sums of money and resources would be required to guarantee the detection of an exotic disease (much less all possible pests and diseases) in its first generation or at the smallest practical area of outbreak. On the other hand, some pests and diseases can be so potentially damaging if an outbreak goes undetected for a sufficient period of time (or before it would be 'naturally detected' in the environment, say by local agricultural producers) that vast expenditures on early detection are indeed justified.

This paper develops a practical model to determine an optimal plant surveillance measure against an exotic pest or disease. The model is practical in the sense that it can be easily calibrated for use in policy-making, provided that required parameter values are available or can be estimated, while being based on the properties of a formal stochastic optimal control framework. Put simply, the idea is to minimize the sum of the direct costs of a pest or disease incursion before detection and during the management period, the cost of the management program given detection of a pest or disease and the cost of the surveillance activity itself through a choice of the area and density of infestation and thus the duration before first detection. Early detection generally implies smaller potential production losses between incursion and lower management cost after a detection occurs. However, the earlier a detection of a pest the more expensive is a plant surveillance activity.

The model is then applied to the case of a potential entry of Papaya Fruit Fly (PPF) in Australia. PPF is recognised as a serious threat to horticultural crops. An outbreak of PPF in Queensland in 1995 resulted in roughly \$43 million Australian dollars of eradication costs over the period 1995 to 1997 (Cantrell, et al., 2003). Since that time the National Office of Animal and Plant Health Australia has implemented an extensive surveillance system designed to detect PPF early. Estimates of an optimal surveillance activity in this paper are used to determine whether the current level of surveillance is appropriate to the case of PPF in Australia.

Part 2 of the paper provides the theoretical model for optimal plant surveillance. Sections 2.1 and 2.2 define the biological growth function used to characterize the growth in area and density of PPF, including the measure of early detection. Section 2.3

sets out the surveillance expenditure function, indicating the various levels of expenditure that correspond to area (and hence time) of spread before first detection. For surveillance measures to be practical it must be the case that early detection occurs before the pest or disease would be detected ‘naturally’ in the environment, in lieu of any publicly funded plant surveillance activity. Section 2.4 details the measure of the production losses that potentially occur both before detection and during the management period (either eradication or containment) given a pest or disease detection. Section 2.5 defines the management cost function and section 2.6 summarizes the objective function used to calculate the minimum of all costs associated with a potential incursion, including the cost of the surveillance activity itself.

Part 3 of the paper provides some background on PPF in Australia, risk assessments and the current surveillance program in Australia. Part 4 calculates, using a genetic algorithm, optimal plant surveillance expenditures for PPF in Australia. Section 4.1 details the key biological parameters used in the model. Section 4.2 indicates the parameters used in the surveillance expenditure function, section 4.3 the production loss function and section 4.4 the disease management cost function. Section 4.5 provides the solution. All parameter values are subject to uncertainty, with defined normal probability distributions and standard errors. Sensitivity results are also papered and discussed. Section 5 provides a comparable cost-benefit calculation for PPF plant surveillance expenditures in Australia and section 6 concludes.

2. Theoretical analysis of a practical optimal surveillance measure

The model has four main components: a biological model to describe the growth in area and density of PPF; a surveillance expenditure function that maps the cost of surveillance to the probable area of spread before detection; a measure of production losses before detection occurs; and losses that result during the management period (either through containment or eradication).

2.1 Biological growth function of disease transmission

(a) Growth of infested area and time length of transmission

Assume that from the initial infested area $N(0)$ and initial density $D(0)$ the pest or disease transmits at a net area growth rate of g and a net density growth rate of z . Following Schaefer (1957), assume that the growth of the pest or disease expansion (in area) follows a Verhulst-Pearl logistic function. At time t the infested area $N(t)$ is given as

$$(1) \quad N(t) = \frac{N_{\max}}{1 + \left(\frac{N_{\max}}{N_0} - 1 \right) e^{-gt}}$$

where N_{\max} and N_0 is the maximum carrying capacity of the disease and the initial infested area, or

$$(2) \quad \lim_{t \rightarrow \infty} N(t) = N_{\max}$$

$$(3) \quad \lim_{t \rightarrow 0} N(t) = N_0.$$

The biological growth curve of insect transmission is indicated in Figure 1. Following this logistic function the infested area starts at N_0 , first grows at an increasing rate to an inflection point, and then grows at a decreasing rate until the infested area reaches a maximum capacity carrying level N_{\max} . Based on equation (1) it is clear that the infested area at time t , or $N(t)$, is positively related to the growth rate of expansion g , the initial infested area $N(0)$ and the maximum carrying capacity N_{\max} ².

Note as well, given equation (1) and biological parameters g , N_0 and N_{\max} , if the value of $N(t)$ is known (through surveillance) then the time length it would take for this level of disease development can be expressed as

$$(4) \quad t = \frac{\left(\ln \frac{N_{\max}}{N_0} - 1 \right) - \left(\ln \frac{N_{\max}}{N(t)} - 1 \right)}{g}.$$

(b) Density Growth

Similarly, assume that the growth of disease density follows a logistic function. At time t the disease density function $D(t)$ is given as

$$(5) \quad D(t) = \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}}$$

where D_{\max} and D_0 is the maximum capacity of disease density and the initial infested density, or

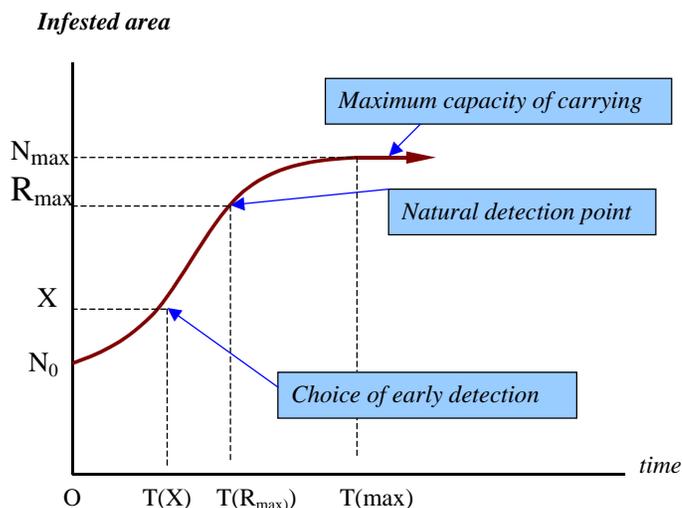
$$(6) \quad \lim_{t \rightarrow \infty} D(t) = D_{\max}$$

$$(7) \quad \lim_{t \rightarrow 0} D(t) = D_0.$$

²Equation (1) can be expressed as $N(t) = \frac{e^{gt} N_{\max}}{e^{gt} + \left(\frac{N_{\max}}{N_0} - 1 \right)} = \frac{e^{gt}}{\frac{e^{gt} - 1}{N_{\max}} + \frac{1}{N_0}}$. Since $(e^{gt} - 1)$ is

always greater than zero a positive relationship between $N(t)$ and N_{\max} is easily established.

Figure 1: Biological growth curve and choice of early detection



2.2 Conditions necessary for surveillance activities and choice of early detection

Protecting agriculture from exotic pests and diseases is vital since an outbreak could result in substantial losses in production, curtail the right of market access and severely harm the environment. Practically, given a limited budget, not all potential exotic plant pests and diseases can be the subject of a surveillance activity. In general, there are at least a number of necessary conditions that need to be satisfied before undertaking a surveillance program. They are:

- (i) The risk of a potential disease incursion must exist and reach a certain minimum probability. At a low or zero risk level of a disease outbreak, the threat is very small and there is no reason to carry out a surveillance activity;
- (ii) The potential social-economic or environment impacts that result from a disease incursion and development should be relatively serious;
- (iii) There is a potential benefit from 'early' detection provided by surveillance. It is not necessary to carry out any surveillance activity if the early detection of the disease does not result in any advantages in terms of lower production losses or less costly disease management options.

Based on Figure 1, it is assumed that the pest or disease can spread for a time period without awareness from the public. It is also assumed that at a given point the 'problem' is naturally detected or recognised by the public before it reaches maximum carrying capacity. To illustrate, in Figure 1, without any surveillance expenditure, the pest or

disease will eventually be ‘naturally’ detected by that public at infestation area R_{max} . The natural detection point R_{max} is less than the point reached at N_{max} .

The point of a surveillance activity is to choose the best level of early detection $T(X)$, or a corresponding infested area X (see Figure 1), before the ‘natural detection’ point. Based on the biological model, the value of $T(X)$ is can be derived as

$$(8) \quad T(X) = \frac{\left(\ln \frac{N_{max}}{N_0} - 1 \right) / \left(\ln \frac{N_{max}}{X} - 1 \right)}{g}$$

using equation (4). Clearly, an X corresponds to the choice of $T(X)$. Earlier detection implies a smaller infested area.

Over the period $T(X)$ disease density growth is estimated from equation (5) Alternatively, using a simple exponential density growth model, $D(X)$ can be approximated derived as

$$(9) \quad D(X) = D(0) * e^{zT(X)}.$$

2.3 Surveillance expenditure function

It is assumed that surveillance activity is effective so that the higher the surveillance expenditure the earlier the detection and the smaller the infested area (X). It is also assumed that: (i) without any surveillance activity the disease would be ‘naturally detected’ by public at R_{max} .; (ii) at some maximum level of surveillance expenditure E_m the disease would be detected at the ‘earliest’ point or at the initial infested area; and (iii) a given surveillance activity can detect the pest or disease (say at X in Figure 1) before at ‘natural’ detection point R_m .

If there are no differences in risk of a pest or disease incursion among all of the potential areas of concern, the marginal benefit of each added dollar spent on surveillance expenditure is constant (i.e., there is a linear relationship between surveillance expenditure and infested area). However, in practice it is natural that there are differences in risk levels (in terms of the probability of a disease incursion) over all potential areas. For example, in the case study of Papaya Fruit Fly there are four different risk levels identified among the areas subject to a potential incursion. In such a case surveillance activities will always be carried out first on the high risk areas and the ‘pay off’ of the first dollar spent on surveillance (or the marginal benefit of an extra dollar spent on surveillance activity) will be higher in the higher risk areas, with the marginal benefit to surveillance activities falling with the potential risk of incursion in an area.

Under the assumption that the marginal benefit of surveillance expenditure will be higher in the first place and decrease continuously until it reaches the point of earliest detection, the surveillance expenditure function $E(X, \eta)$ per year is a hyperbola which asymptotes to the vertical and horizontal axes (see Figure 2), given by

$$(10) \quad E(X, \eta) = \frac{E_m (R_{\max} - X)}{R_{\max} (\eta X + 1)}$$

where $E(X, \eta)$, E_m , R_m , and X is the surveillance expenditure corresponding to X infested area (when the disease is detected), the maximum surveillance expenditure for the 'earliest' detection, the maximum infested area at the 'latest' detection, and the infested area under a given surveillance system. The value η represents a coefficient of surveillance effectiveness, reflecting the marginal benefit of each extra dollar spent on surveillance. From equation (9) it follows that

$$(11) \quad \lim_{X \rightarrow 0} E(X, \eta) = E_m \quad \lim_{X \rightarrow R_m} E(X, \eta) = 0$$

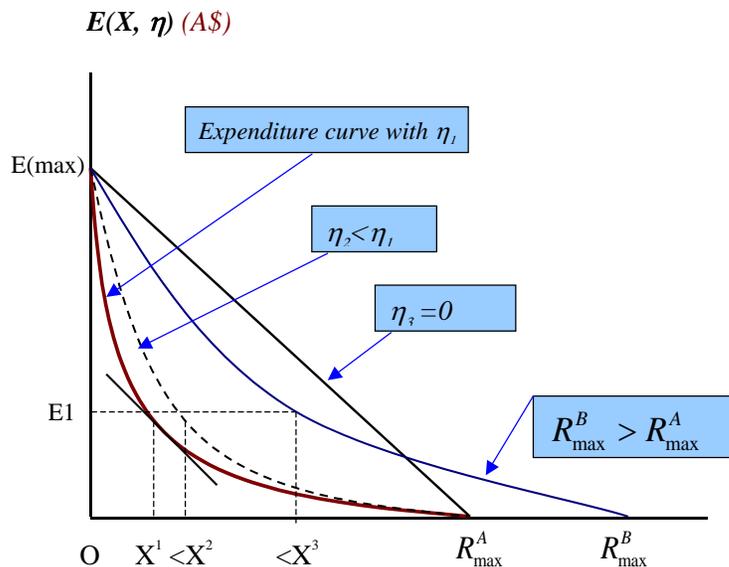
and

$$(12) \quad \frac{\partial E(X, \eta)}{\partial X} < 0.$$

so that decreasing the area of spread of the disease or pest before detection clearly requires additional expenditures on surveillance activities.

From Figure 2, everything else equal, the higher η the lower the expenditure on surveillance for a given area X , or the more convex is the expenditure function. With $\eta = 0$ that curve is linear or the marginal benefit of surveillance expenditure is constant.

Figure 2: Surveillance expenditure function



The aggregate present value of surveillance expenditures until the disease is detected at $T(X)$ is thus given as

$$(13) \quad TE(X, \eta) = \sum_{t=1}^{T(X)} \frac{1}{(1+r)^t} \frac{E_m(R_m - X)}{R_m(\eta X + 1)}$$

where r is the discount rate and $T(X)$ is given as in equation (8).

2.4 Potential production loss and trade restrictions

Once a potentially harmful pest or disease is detected there are two management possibilities: eradication or containment. In this study it is assumed that the appropriate option is eradication.³ In this case potential production losses include (i) the production loss before the pest or disease is detected; and (ii) the production loss during the period of disease management⁴.

(a) Production cost before detection

This potential production cost before detection depends on the probability of disease outbreak under the current surveillance system (p), the time length of disease development and the production loss per unit area c_p . At time t the production cost caused by the disease is a function of cost per unit area and the size of infested area, or

$$(14) \quad C_p(t) = p * c_p(t) * N(t)$$

where $c_p(t)$ is the production loss per unit area and $N(t)$ is the infested area at time t as given as in equation (1).

Assume as well that the production loss per unit area is a function of disease density so that

$$(15) \quad c_p(t) = c_p(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}}$$

where $c_p(0)$ is the initial production cost unit per an unit of area at the initial density $D(0)$. Substitution gives the potential production loss per year as

$$(16) \quad CP_p(t) = p * c_p(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}} * \frac{N_{\max}}{1 + \left(\frac{N_{\max}}{N_0} - 1 \right) e^{-gt}}$$

³For the case if containment, rather than the cost of eradication one needs to consider permanent containment costs (production loss, trade losses and so on).

⁴It is argued that potential trade losses should be included and especially so during a containment period or the period of time over which eradication takes place. There is no trade loss however before the outbreak of the disease is declared. Therefore trade loss (if it occurs) is considered only during the disease management period.

Under a given surveillance measure the aggregated present value of production loss since the disease outbreak until being detected over $T(X)$ is given as

$$(17) \quad CP_P = \sum_{t=0}^{T(X)} \frac{1}{(1+r)^t} P * c_P(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}} * \frac{N_{\max}}{1 + \left(\frac{N_{\max}}{N_0} - 1 \right) e^{-gt}}$$

where $T(X)$ is given in equation (8)⁵. Clearly,

$$(18) \quad \frac{\partial TC_P}{\partial X} > 0$$

or production losses are larger the larger the infested area.

(b) Production loss during the period of disease management

This loss measured during the period of disease management is given as

$$(19) \quad CP_E = \sum_{i=1}^{T_M} \frac{1}{(1+r)^{T(X)+i}} \phi * X * AR$$

where T_M is the time length required to manage the disease; ϕ is a management coefficient indicating the buffer management area included in control or eradication; and AR is average total production revenue per unit area, including lost revenue from both domestic sales and any trade ban that may be imposed during the management period. There are two assumptions made for estimating these cost component: (i) the disease management area includes the infested area and the buffer zone surrounding it; and (ii) during the period of disease management there is revenue loss in the management area. For simplification, T_M is taken as exogenous in equation (19) regardless how large the infested area. However, in many cases it can be set as a function of X . The larger X , generally speaking, the longer the time taken for disease management.

(c) Total potential production loss

Total potential production losses are thus given by

$$(20) \quad TCP = CP_1 + CP_2 = \sum_{t=0}^{T(X)} \frac{1}{(1+r)^t} P * c_P(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}} * \frac{N_{\max}}{1 + \left(\frac{N_{\max}}{N_0} - 1 \right) e^{-gt}} + \sum_{i=1}^{T_M} \frac{1}{(1+r)^{T(X)+i}} \phi * X * AR$$

⁵It is argued that the production loss could continue during the eradication time, in this case the production loss is added the production loss resulted during the eradication period.

It is argued that the second component of the potential production cost in practice is important since production revenue is lost during disease management, both domestically and from trade bans internationally. However if disease management is effective immediately (or in a very short period of time), without any revenue loss, then the potential production loss is only the first component of equation (20)

2.5 Disease management cost function

Following the eradication option then the potential management cost to control a disease incursion depends on the probability of disease outbreak, how early the disease is detected and the management cost per unit area $c_M(t)$. At $T(X)$ the potential disease management cost (C_M) is given as

$$(21) \quad C_M = p * c_M(t) * X$$

where $c_M(t)$ is the management cost per unit area.

Assume that the cost per unit area is a function of disease density at $t(X)$, or

$$(22) \quad c_M(t) = c_M(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}}$$

Substituting equation (22) into (21), the disease management costs for a surveillance measure given infested area X area is given as

$$(23) \quad C_M(X) = p * c_M(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zT(X)}} * X$$

where $c(0)$ is the initial cost unit per unit of area at $D(0)$ density and $T(X)$ is given in equation (8). Costs clearly increase with area, or

$$(24) \quad \frac{\partial TC_M}{\partial X} > 0.$$

At $T(X)$ the present value of the disease management cost TC_M in equation (23) is

$$(25) \quad TC_M(X) = \frac{1}{(1+r)^{T(X)}} p * c_M(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zT(X)}} * X.$$

for r the discount rate.

2.6 An optimal surveillance measure

The objective now is to minimize the total present value of all costs over T years as a sum of (i) the aggregated surveillance expenditures ($TE(X, \eta)$); (ii) the potential production costs caused by disease development before being detected; and (iii) the potential cost of the disease management if it is detected at the ‘early’ level of X, or

$$(26) \quad \min_{stX} TC = \sum_{t=1}^{T(X)} \left(\frac{1}{(1+r)^t} \right) \left(\frac{E_m (R_m - X)}{R_m (\eta X + 1)} \right) \quad \leftarrow \text{Surveillance cost}$$

$$+ \sum_{t=0}^{T(X)} \frac{1}{(1+r)^t} P^* c_P(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zt}} * \frac{N_{\max}}{1 + \left(\frac{N_{\max}}{N_0} - 1 \right) e^{-gt}} + \sum_{i=1}^{T_M} \frac{1}{(1+r)^{T(X)+i}} \phi^* X * AR \quad \leftarrow \text{Potential production cost}$$

$$+ \frac{1}{(1+r)^{T(X)}} P^* c_M(0) * \frac{D_{\max}}{1 + \left(\frac{D_{\max}}{D_0} - 1 \right) e^{-zT(X)}} * X \quad \leftarrow \text{Potential management cost}$$

Equation (26) applies to most circumstances. However, in practice, many cases of plant pests and diseases imply, for example, that density growth may not affect management costs or the potential production cost is small or zero during the management period. Equation (26) is easily adjusted for these simpler cases.

3. Background of Papaya Fruit Fly in Australia, risk assessment and the current surveillance system in Australia

Fruit flies are the world’s worst pests of fruit and fruiting vegetables, causing millions of dollars worth of damage a year. Australia has a number of native fruit flies, but most of these do not attack crops of economic significance. In contrast, exotic fruit flies present in neighbouring countries can infest commercial crops, causing crop devastation and trade disruption and requiring expensive eradication campaigns.

Early detection is the best means to achieve speedy and cost-effective eradication, and Australia has an extensive fruit fly surveillance program. Fruit fly traps are set in more than 1600 locations across Australia to monitor for exotic fruit flies, including trapping in remote northern locations by AQIS’s Northern Australian Quarantine Strategy (NAQS). Trapping also provides evidence to overseas trade partners of Australia’s freedom from particular fruit fly species (Department of Agriculture, Forest and Fisheries (DAFF), 2009).

3.1 Background of Papaya Fruit Fly

Papaya Fruit Fly is recognised as a serious pest to horticultural crops in South East Asia. It is officially recorded as endemic to Thailand, Malaysia, Singapore, Borneo, Indonesia, Christmas Island and Papua New Guinea (Drew and Hancock 1994). More than 4,000 species of Fruit Fly are known worldwide. Papaya Fruit Fly (*Bactrocera papayae*: PFF) is one of 60 species of the Oriental Fruit Fly complex (*Bactrocera dorsalis*). Virtually all fruit (fruits containing seeds) and vegetables can be attacked by PFF and are considered hosts for carrying PFF (Monzu, Hardie and Johnston, 2002 and ABARE 1995).

PFF is about the same length as a common housefly but more slender. It grows to 7mm in length and has clear wings, a generally black chest and a paler abdomen with a distinctive black T-shaped marking on the back. Fruit flies may live for several months and are capable of reproducing throughout their life span. Like most tropical Fruit Fly species, Papaya Fruit Fly multiplies rapidly and can quickly spread over large distances. Adult female flies lay their eggs just under the skin of fruit, depositing fruit decaying bacteria at the same time. Within one to two days the eggs hatch into maggots (larvae), which feed on the decaying fruit, causing premature fruit drop. Considerable damage can occur inside the flesh before obvious signs of infestation can be seen on the fruit. The most obvious signs of infestation are small, discoloured patches on the skin, which develop from punctures or 'stings' made by the female as she lays her eggs. It takes 7-12 days for the larvae to leave the fruit to develop into pupae in the soil. Adults emerge from the pupae in another 10 to 14 days and become sexually mature after one to two weeks. They live for several months and are capable of reproducing throughout their life span. Like most tropical Fruit Fly species, papaya Fruit Fly multiplies rapidly and can disperse over large distances. It is capable of establishing in any of the mainland States of Australia (Monzu, Hardie and Johnston, 2002).

3.2 Potential threat of Papaya Fruit Fly outbreak in Australia

The threat of PFF outbreak depends on the risk of PFF arrival and its likelihood of establishment. The most important risk of disease incursion in Australia is from the Torres Strait Islands, because of the short distance from the PFF infested Pacific islands (e.g., Papua New Guinea). The number of PFF detected in this area is extremely high. For example, the number of PFF found in routine inspections by Australian Quarantine and Inspection was 309, 1156, 456, 113 and 118 in 1995, 1998, 1999, 2001 and 2002 (see Appendix, Table A1). Without surveillance and local control activities the number of PFF would increase dramatically and quickly expand to islands in the area and eventually to mainland Australia.

There is also the high risk of PFF outbreak in Australia from the large number of international tourists from PFF endemic countries (carrying infested fruits). Every year about 3.5 million international passengers from PFF endemic countries travel to Australia and are potential PFF carriers. In recent years, PFF was caught by surveillance in mainland Australia several times, e.g., the years 1993, 1995, 1999 and 2002 (Agriculture, Fishery and Forestry of Australia (AFFA), 1999 and Agriculture, Fishery and Forestry of Australia, websites, 2002).

It is not unrealistic to assume that PFF could be identified in traps as far away as Western Australia, South Australia or Tasmania. Many of these PFF host commodities are grown in horticulture production areas throughout Australia. Should PFF become established in these areas, both international and interstate trade would be subjected to stringent quarantine measures. These measures would significantly impact on the cost of producing these commodities. This could cause a loss in business profits, increase unemployment and reduce future investment in the Australian horticulture industry.

In March 1993, PFF was detected for the first time in Australian territory on the islands of Saibai, Boigi and Dauan, adjacent to the PNG coast, and on Stephen and Darnley Islands, further east in Torres Strait. Successful eradication programs have been carried out on Stephen and Darnley Islands. Since then most of the inhabited islands of Torres Strait and the northern tip of Cape York Peninsula have been regularly monitored by trapping and eradication measures applied as necessary.

The first outbreak of PFF on mainland Australia was detected in the north Queensland in 1995, and resulted in an eradication campaign with total costs of A\$43 million over a total management area of 80,000 km² (Cantrell, Chadwick and Cahill, 2002). In November 1997, PFF was detected in the Darwin suburb of Berrimah. All necessary quarantine and surveillance measures took place in the area extending 50km² in radius from the detection point. One month later PFF was detected again at Humpty Doo, some 50 km southwest of the first detection. The 13-month eradication program required to get rid of PFF over the management area of 6,200 km² cost around 3 million dollars (Smith, 2002). Because of the early detection provided by the current trap surveillance program the area of disease management and the management cost was more than ten times smaller than the outbreak in 1995.

Over the years millions of dollars have spent for the early detection of PFF. Similar to any expenditure on surveillance activities there is an essential tradeoff to consider. On one hand it may be not economic (or indeed impossible) to spend vast monies to detect PFF at the earliest possible stage. On the other hand it can potentially cost Australian agriculture large if not excessive damages if PFF is detected too late (the eradication program in 1995 is an example). An optimal surveillance expenditure needs to be determined.

3.3 The current Papaya Fruit Fly surveillance system in Australia

The national exotic Papaya Fruit Fly program (as part of the National Exotic Fruit Fly Trapping Program) serves as an 'early warning system' to detect and identify incursions of targeted exotic fruit fly pests entering through international pathways at ports and associated urban areas. The 5 km grid density of the general surveillance network is the density at which eradication is considered achievable once an incursion is detected (Roberts and Coyle, 2002).

The objective of the PFF surveillance system is "to enable the early detection of exotic fruit fly incursions in areas exposed to an initial entry and establishment, so that a successful and cost-effective eradication campaign can be developed before populations spread to production areas" (Roberts and Coyle, 2002). A surveillance grid using

pheromone traps of Methyl Eugenol (ME) is used for PFF and other exotic pests of the Oriental Fruit Fly complex (*Bactrocera dorsalis*).

Depending on the target areas for surveillance (high, medium and normal risk levels), different densities of trap grid are used. In the high-risk area, the density of traps varies from one trap per 200 to 400-metre grid. In the medium risk area (the horticultural production areas) the density of traps is one trap per 800 to 1.5 km grid intersection. In the normal risk area one trap per 5 km grid intersection is used for port of entry monitoring (required by Australian Quarantine and Inspection Service (AQIS)). The details of PFF surveillance trapping system are indicated in Appendix, Table A2.

The two main sources of risk of PFF incursion are from the Torres Strait Zone and travellers. The sensitive areas, which are targeted under surveillance, are the port areas, the key travel paths and the nearby areas. At present, based on the objective to detect PFF in the first, second or third generation, different alternative trap grids in each state or in each areas of a state are chosen (see Appendix, Table A2). The surveillance sensitive areas and the number of traps in each state are indicated in table 1. Details of number of traps for each grid size are indicated in Appendix, Table A2. The surveillance system in the Torres Strait Zone is extremely important since the number of flies detected every year is very high (see Appendix, Table A1).

The summary of surveillance costs is indicated in table 1 below. The surveillance cost is computed from the direct costs of lures, installing, monitoring, diagnostics and travel, adding around 30 per cent for indirect costs (including publicity, awareness campaigns, laboratories, etc.).

Table 1: Surveillance system of Papaya Fruit Fly in states of Australia

State	Number of trap	Direct cost*	Surveillance sensitive areas
	(no)	(\$)	km ²
New South Wales	216	\$273,000	5,400
Queensland	180	\$209,000	4,500
Victoria	441	\$88,800	11,025
Western Australia	167	\$78,500	4,175
South Australia	587	\$62,400	14,675
Tasmania	149	\$26,500	3,725
Northern Territory	98	\$113,900	2,450
Torres Strait Special Zone	40	\$529,300	582
Total	1878	\$1,381,000	46,532

Source: Estimated from the statistics provided from National Office of Animal and Plant Health, Agriculture, Fishery and Forestry of Australia (AFFA), 2002; Queensland Forestry Research Institute, 1998; Agriculture of New South Wales; Department of Primary Industries of Queensland, 2002 and Northern Australian Quarantine Services, 2002.

Note: The cost includes the direct expenditure of lures, installing, monitoring, diagnostic and travelling, excluding indirect costs of administration or other management.

Average expenditure per trap for surveillance (including installing, monitoring, and diagnostics) and travelling to site varies significantly from area to area. The travel cost is highest in Torres Strait Special Zone because of the expense of helicopter cost (with a rental of \$6,000 per day for over 51 days per year). The average cost of surveillance per trap is highest in Torres Strait Special Zone and Queensland, where the high density of other fruit flies requires much effort on diagnostics and identification (\$1,200 and \$343 respectively). The cost in New South Wales, Victoria and South Australia is smaller at \$103 for New South Wales and Victoria and \$51.5 for South Australia.

4. A practical optimal surveillance measure for PPF in Australia

Applying the theoretical framework in section 2 for the case study of Papaya Fruit Fly in Australia the optimal level for surveillance can be estimated. It is first important to determine and estimate all parameters required for the solution procedure. Following the theoretical framework, the set of parameters used for solving can be arranged into four groups: (i) risk assessment and key biological facts; (ii) the Papaya Fruit Fly surveillance expenditure function; (iii) the production loss function; and (iv) the disease management costs function.

4.1 Risk assessment and key biological parameters

The most likely entry route of the PPF into Australia is believed to be from the Torres Strait Zone. Based on known facts regarding PPF incursions in Australia since 1990 it is assumed that the probability of PPF incursion in the mainland is (conservatively) one occurrence every five years. Assume as well that this probability is characterized by a normal distribution with a standard deviation of 10 per cent, or $N(0.2, 0.02)$ (see table 2).

The growth rate of PPF expansion is estimated from reproduction rates throughout the PPF life span and known estimates of catching PPF of differing generations under different trap grids. Based on AFFA (1999) and Monzu, Hardie and Johnston (2002), it takes four weeks to produce a new generation. Therefore after four weeks PPF develops from the initial area of outbreak (1.5 km²) to an infested area of 2.25 km² (the first generation), and eight weeks to the infested area of 25 km² (the third generation). Therefore the growth rate of expansion is roughly 15 to 20 per cent per month (sensitivities of this parameter will be also considered).

Based on the analysis of AFFA (1999) regarding the average number of flies per km² since the first week of outbreak and taking 100 per cent as the maximum density carrying capacity, the initial density in the first week of outbreak is given as 2 per cent. The growth rate of density is estimated as 60 per cent per month, or it would take around eleven months for PPF to reach maximum density levels since the first outbreak. Assumed probability distributions, standard deviations and all main parameters are indicated in table 2.

The initial area of disease management is assumed to be a radius of 15 km. It is also assumed that if PPF develops from a 5 km distance (the initial 5 km trap grid), with a 10 km 'buffer' radius, then the initial management area of PPF development is around 700 km² (estimated from De Lima, 2002).

Table 2: Probability of PFF outbreak and biological parameters

Contents	Unit	Denotation	Parameters
1. Probability of outbreak in the Australian mainland		p	N(0.2, 0.02)
2. Growth rate of expansion	%/month	g	N(0.175, 0.02)
3. Growth rate of density development	%/month	d	N(0.4, 0.04)
4. Initial density (% of the maximum density)	%		2
5. Initial area of development	km ²	N ₀	700

4.2 Papaya Fruit Fly surveillance expenditure function

Next, consider the surveillance expenditure function analyzed in section 2.2 (see table 3). Without any surveillance measures the number of traps and surveillance expenditures is essentially zero. At the time PFF was naturally detected in Queensland in 1995, the infested area in Australia was calculated to be 80,000 km² (Cantrell, et al., 2002).

Table 3: Parameters of surveillance measure

Surveillance measures	Number of trap (no)	Total cost* (\$)	Potential managed area km ²
1. Without quarantine measures in Torres Strait Zone & the mainland	0	\$0	80,000 (natural detection)
2. Maximum level of surveillance measure	20,681	\$7,100,000	700 (minimum point)
3. Current level of surveillance measure	1,878	\$1,300,000	6,200

At a maximum level of surveillance, assume that PFF would be detected at the ‘earliest’ point or in the first week of the first generation. The maximum surveillance measure would require applying (at least) a 400-meter grid size of pheromone traps. In such a case around 20,600 pheromone traps would be needed to cover all of the surveillance sensitive areas. Based on the cost of traps and trap-related expenditure, the maximum surveillance expenditure is thus about \$7.1 million.

At present about 1,880 traps (including both Commonwealth and state traps) are installed (see table 1) with the total cost of surveillance of about \$1,300,000 per year.

Based on the PFF incursion in 1997 (Smith, 2002) it is indicated that under the present surveillance measure the potential management area is up to 6,200 km² before PFF would be detected. Based on equation (12) in section 2.2, the coefficient η of the surveillance expenditure function of surveillance is thus estimated at 0.0012.

4.3 Production loss function

Given a surveillance measure, a PFF development could implicitly expand to an infested level causing significant ‘unaware’ damage to horticulture. As discussed in section 2.3, this loss depends on the size of infested area, the density of disease development and the initial average cost of the disease or pest per km².

There are four key assumptions used in this section. First, the local value of horticulture used in this paper is the Local Value (direct farm value) rather than Gross Value of Production. It is assumed that the cost of disease would only occur at the farm level (directly affecting fruits or vegetables), and not to the indirect farm sector (such as transportation, retail, etc.). Second, it is assumed that the riskiest area in terms of PFF outbreak is Queensland because this state is closest to Torres Strait and has the most suitable natural conditions for PFF development. Third, only horticultural industries subjected to PFF throughout Australia are included in this analysis. Based on this assumption we calculate the average horticultural value per km² in Australia (including all fruit and vegetable industries, based on measures from Queensland statistics). Finally, we assume that the potential infested area of PFF excludes all desert areas in the region.

The local value of fruit and vegetable industries, which are potential hosts of PFF, in Queensland is 798.6 million dollars, accounting for around 20 per cent of Australia as a whole (Australian Bureau of Statistics (2002), Appendix, table A3 and A4)⁶. The average value of horticultural industries, which are potential hosts for PFF, is about \$536 per km² in Queensland. This value is applied generally to all potential PFF host horticultural areas in Australia.⁷

The potential production loss of PFF is calculated by equation (16). It is assumed that at the maximum level of PFF density, the cost of PFF per km² on average could up to 90 percent of the average horticultural value (\$536 per km²) or around \$480. Using the parameters in table 2, it is estimated the initial average cost per km² starts from \$9.6 at minimum density and growth to \$460 per km² at the maximum density level.

4.4 Disease management cost function

With an outbreak of PFF in Queensland in 1995 it was determined at the time that the best management solution is eradication (ABARE, 1995). An effective eradication

⁶ The term of ‘horticultural industries’ indicated in this report refers to the host PFF industries only.

⁷ Average value of horticulture farms per km² is much higher but the potential infested area could be much larger. For example, the outbreak of PFF in Queensland in 1995 covered about 19,000 km² but the ‘pure’ orchards and vegetable areas accounted for less than 3 per cent of that total area (estimated from Cantrell, *et al.*, 2002 and ABS, Queensland Agriculture 1998).

campaign involves bait spraying, male annihilation and sterile insect release in the infested area and buffer zone. Specific local quarantine and surveillance actions are also required (Cantrell 2002). Based on the eradication campaign in Queensland in 1995, eradication action was taken regardless of the level of PFF density (i.e., areas were blanket sprayed regardless of density). The management cost of PFF is determined by equation (22), see section 2.4, where the infested area is a function of the PFF growth rate of expansion as described in equation (1). In Australia the average cost of PFF management is around \$539 per km² (estimated from Cantrell 2002 with a CPI deflator at 2000 prices (Australian Bureau of Statistics 2002)).

4.5 Solution for optimal level of plant surveillance

The minimization of equation (23), through a choice of X and thus $T(X)$, is obtained with a genetic algorithm. The approach provides a multi-dimensional and globally robust search mechanism with which to optimize over a decision process involving uncertainty in parameter values. Solutions and sensitivity results are indicated in table 4.

Given all parameter values and assumed probability distributions, that optimal result in Table 4 is a plant surveillance (direct) cost of \$2,083,000 per year, with a mean surveillance area of 4,022.6 km². This can easily be translated into a number of traps and their distribution by risk area. The current level of plant surveillance expenditure in Australia is \$1,381,000.

Given uncertainty over all results, a Monte Carlo exercise on mean values given probability distributions is summarized in Figure 3. Optimal surveillance expenditures range from A\$1.8 to A\$2.5 million with a combined probability of roughly 94 per cent. Under this surveillance measure PFF would be detected at the size of infested area of around 4,000 km², on average. Clearly in high-risk areas grid size will be much smaller. It should be noted that without surveillance PFF would be detected 'naturally' at a infested area of 80,000 km². At the optimal surveillance choice minimum total costs as a sum of surveillance, production loss and management costs ranged from A\$2.7 million to A\$3.1 million, with a probability of 95 per cent (Figure 4).

Sensitivity results are also indicated in Table 4. The sensitivity of the probability of PFF outbreak (scenarios 1 and 2) indicates that the higher probability of PFF outbreak the larger should surveillance expenditure be. If the probability of PFF outbreak is once per two years then the optimal surveillance expenditure should increase to A\$2.4 million (mean value) instead of A\$2 million as in the current solution. However if the probability of PFF outbreak is about once over 12.5 years (rather than 5 years at present parameters) then the optimal surveillance expenditure does not vary much, at A\$1.9 million dollars per year.

Figure 3: Probability distribution for surveillance expenditures

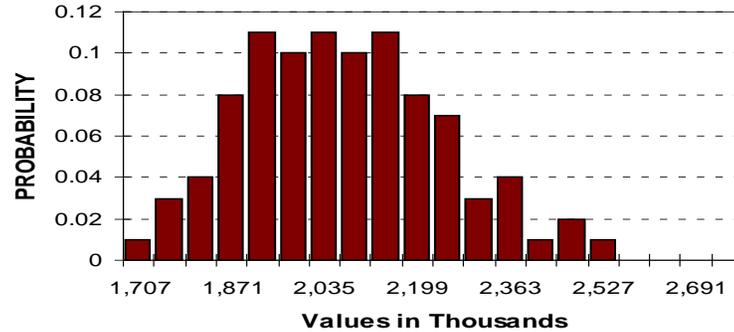
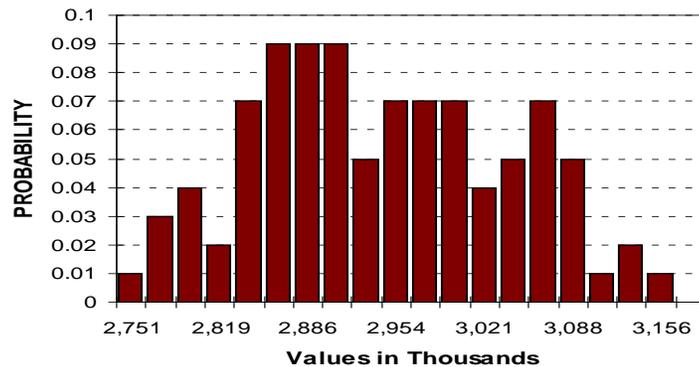


Figure 4: Probability distribution of total potential cost of PPF



Sensitivity on the level of natural detection point (scenarios 3 and 4) indicates that the size of the natural detection point does not alter optimal surveillance expenditure a great deal, indicating that the surveillance expenditure curve is very steep around the optimal solution point. At this point the marginal benefit of surveillance expenditures in terms of reducing the potential infested area is thus quite small.

Sensitivity of growth rate of PPF (scenarios 5 to 6) indicates large differences in optimal solutions. In general, the higher growth rate of PPF the faster it will become detected. With a much slower growth rate of transmission, optimal surveillance expenditure is much higher. In this case PPF develops more slowly, with the longer period of time for the potential cost of production losses to be detected.

Finally, the average production cost or production losses from PPF per area (scenarios 7 and 8) shows that the optimal surveillance expenditure is quite sensitive to this parameter. A fall in production costs to \$200 per km² results in a dramatic fall in surveillance expenditure to \$360,000.

Table 4: Sensitivity analysis and (generic algorithm) optimal solutions

	Parameter sensitivity			Optimal genetic algorithm solution			
	Probability of PFF outbreak	Natural maximum detection managed area	Growth rate of PPF	Average prod cost \$/km2 at max density	Choice of surveillance measure area	Min of total costs	Surveillance cost/year
	p	R _m	g	c _p (max)	mean X	mean TC	mean TE
Main result	N(0.2, 0.02)	N(80,000, 8,000)	N(0.18, 0.02)	N(536.3,53.6)	4,022.6	\$2,948,000	\$2,083,000
Sensitivity of the probability of PFF outbreak (p=(1,0)							
Scenario 1	N(0.5, 0.02)	N(80,000, 8,000)	N(0.18, 0.02)	N(536.3,53.6)	3,382.3	\$4,238,000	\$2,420,000
Scenario 2	N(0.08, 0.02)	N(80,000, 8,000)	N(0.18, 0.02)	N(536.3,53.6)	4,286.4	\$2,337,000	\$1,968,000
Sensitivity of the maximum PPF managed area 'naturally detected' (km2)							
Scenario 3	N(0.2, 0.02)	N(120,000,8000)	N(0.18, 0.02)	N(536.3,53.6)	4,054.7	\$2,776,000	\$2,050,000
Scenario 4	N(0.2, 0.02)	N(40,000,8,000)	N(0.18, 0.02)	N(536.3,53.6)	3,872.2	\$3,470,000	\$2,220,000
Sensitivity of PPF growth rate of expansion (%/month)							
Scenario 5	N(0.2, 0.02)	N(80,000, 8,000)	N(0.40, 0.02)	N(536.3,53.6)	6,233	\$2,729,172	\$1,388,983
Scenario 6	N(0.2, 0.02)	N(80,000, 8,000)	N(0.30, 0.02)	N(536.3,53.6)	2,896	\$2,599,550	\$1,976,852
Scenario 6	N(0.2, 0.02)	N(80,000, 8,000)	N(0.10, 0.02)	N(536.3,53.6)	1,730	\$4,444,000	\$4,072,000
Sensitivity of average production cost (\$/ha)							
Scenario 7	N(0.2, 0.02)	N(80,000, 8,000)	N(0.18, 0.02)	N(1000,53.6)	3,800	3,359,000	2,190,000
Scenario 8	N(0.2, 0.02)	N(80,000, 8,000)	N(0.18, 0.02)	N(200,53.6)	27,872	5,867,000	360,000

4. Concluding remarks

This paper develops a practical model to determine an optimal plant surveillance measure against an exotic pest or disease. Put simply, the idea is to minimize the sum of the direct costs of a pest or disease incursion before detection and during the management period, the cost of the management program given the detection of a pest or disease and the cost of the surveillance activity itself through a choice of the area and density of infestation, and thus the time length before first detection. Clearly, the earlier a detection of a pest the more expensive is a plant surveillance activity. Early detection however also generally implies smaller potential production losses before detection occurs and lowers management costs after detection.

The model is applied to the case of a potential entry of Papaya Fruit Fly (PPF) in Australia. PPF is recognised as a serious threat to horticultural crops. An outbreak of PPF in Queensland in 1995 resulted in roughly \$43 million Australian dollars of eradication costs over the period 1995 to 1997 (Cantrell, et al., 2003). Since that time the National Office of Animal and Plant Health Australia has implemented an extensive surveillance system designed to detect PPF early. Estimates of an optimal surveillance activity in this paper are used to determine whether the current level of surveillance is appropriate to the case of PPF in Australia.

Given all parameter values and probability distributions, that optimal result is a plant surveillance (direct) cost of \$2,083,000 per year, with a mean surveillance area of 4,022.6 km². The current level of plant surveillance expenditure in Australia is \$1,381,000.

Accounting for standard errors, optimal surveillance expenditures range from A\$1.8 to A\$2.5 million with a combined probability of roughly 94 per cent. Under this surveillance measure PPF would be detected at the size of infested area of around 4,000 km², on average. Clearly in high-risk areas grid size will be much smaller. At the optimal surveillance choice minimum total costs as a sum of surveillance, production loss and management costs ranged from A\$2.7 million to A\$3.1 million, with a probability of 95 per cent.

Sensitivity results indicate that optimal surveillance expenditures are very insensitive to changes in the probability of an outbreak of PPF and the area of PPF spread under 'natural detection', or in lieu of any surveillance expenditures. However, optimal surveillance expenditures are very sensitive to production losses per area both before and after detection and the growth rate of the pest or disease. For the biologist the growth rate of PPF is the most important parameter to determine for the economist, average production losses are important to the solution.

Appendix

Table A5: Papaya Fruit Fly detected in Torres Strait

Site	Sum of number of detection counted										Grand Total
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	
Saibai I.	5	16	111	18	9	252	268	8			687
Boigu I.	6	46	92	11	16	317	89	22	4	2	605
Dauan I.	4	21	90	1	14	407	5	4	1		547
Darnley I.					12	103	14				129
Buzi									124		124
Stephen I.	4		11			12	10	15	1	26	79
Yam I.				2		23	4	19		18	66
Deliverance I.							27		1	4	32
Mer I.			2			1	2		1	23	29
Mabuiag I.						9	13	2		4	28
Moa I.					1	20	1	3			25
Yorke I.			3	1	2	3	2			14	25
Dalrymple I.				1		1	3		1	15	21
Gabba I.							4	1		7	12
Badu I.						4	4				8
Coconut I.							5				5
Nagir I.						1	1			2	4
Tudu I.						1	1			1	3
Thursday I.						1	1				2
Bamaga										1	1
Dawer I.										1	1
Hammond I.						1					1
Horn I.							1				1
Sue I.							1				1
Total	19	83	309	34	54	1156	456	74	133	118	2436

Source: Northern Australian Quarantine Services, 2002.

Table A6: Papaya Fruit Fly surveillance in Australia

	Area km2	Number of pheromone (ME) traps for each gird size					Total	
		200m	400m	800m	1.2km	1.5km	5km	
New South Wales,	800,640						216	216
Queensland, incl	1,730,068						157	180
• Weipa area						3	1	
• Special Zone			3			3		
• National Parks			10				3	
Victoria	227,420						441	441
Western Australia	2,529,880		27				140	167
South Australia	983,480			125		361	101	587
Tasmania	68,400				149			149
Northern Territory	1,349,130			30			68	98
ACT	2,360							
Jervis Bay Territory	70							
Torres Strait	582	7	9			11	13	40
Total	7,692,030	7	49	155	149	378	1,140	1,878

Source: National Office of Animal and Plant Health, Agriculture, Fishery and Forestry of Australia (AFFA), 2002.

Note: National Parks including a number of national parks up in the Cape York Area.

Table A7: Local value of fruit industries in Australia and Queensland in 2000

Commodity	Local Value of Australia (\$m)	Local Value of Queensland (\$m)	Average price in Queensland (\$/kg)
Citrus			
• Oranges	214.8	10.4	0.83
• Lemon and lime	19.1	5.3	0.86
• Mandarins	70.7	46.0	1.01
Pome			
• Apples	220.3	20.2	0.78
• Pears (excl. Nashi)	63.7	1.0	1.03
Stone			
• Apricots	30.0	0.1	1.37
• Cherries	36.7		
• Nectarines			
• Olives	3.3		
• Peaches	67.1	4.0	1.27
• Plum and prunes	38.1	2.3	1.57
Other orchard fruit			
• Avocados	43.9	25.4	2.22
• Mangoes	71.5	48.1	1.82
Blueberries	25.0	(b)	(b)
Strawberries	85.0	21.9	6.28
Tropical			
• Bananas	207.1	148.1	1.04
• Pawpaws	3.9	3.8	1.20
• Pineapples	38.4	38.4	0.31
Grapes	1065.0	13.9	(b)
Other fruit n.e.c	65.8	14.2	-
Total	2,369.4	403.1	

Sources: Australian Bureau of Statistics (2002).

Note: (b) Data not collected.

Table A8: Local value of vegetable industries in Australia and Queensland in 2000

Commodity	Local Value of Australia (\$m)	Local Value of Queensland (\$m)	Average price in Queensland (\$/kg)
Asparagus	87.9	7.6	6.26
Beans, french and runner	39.0	26.2	1.83
Beetroot	6.8	6.2	0.22
Broccoli	41.2	5.2	1.32
Cabbages	13.4	2.6	0.32
Capsicum, chillies and peppers	44.9	35.4	1.36
Carrots	114.3	9.5	0.50
Cauliflowers	40.2	3.7	0.50
Celery	14.9	3.6	0.44
Cucumbers	13.5	1.7	0.75
Green peas (pod wt)	13.7	0.9	0.90
Lettuces	67.4	22.0	0.76
Marrow, squad and zucchini	18.6	10.6	1.34
Melons			
• Water	26.4	14.1	0.38
• Rock and cantaloupe	48.4	25.7	0.77
Onions, white and brown	97.2	9.0	0.53
Parsnip	8.4	-	-
Potatoes	317.5	32.6	0.36
Pumpkins	39.2	15.5	0.40
Sweet corn	21.6	8.4	0.60
Tomatoes	150.5	79.5	1.25
Other vegetable	267.0	75.5	-
Total	1,492	395.5	

Sources: Australian Bureau of Statistics (2002).

Note: (b) Data not collected.

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