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A benefit–cost framework for responding to an incursion of Varroa destructor

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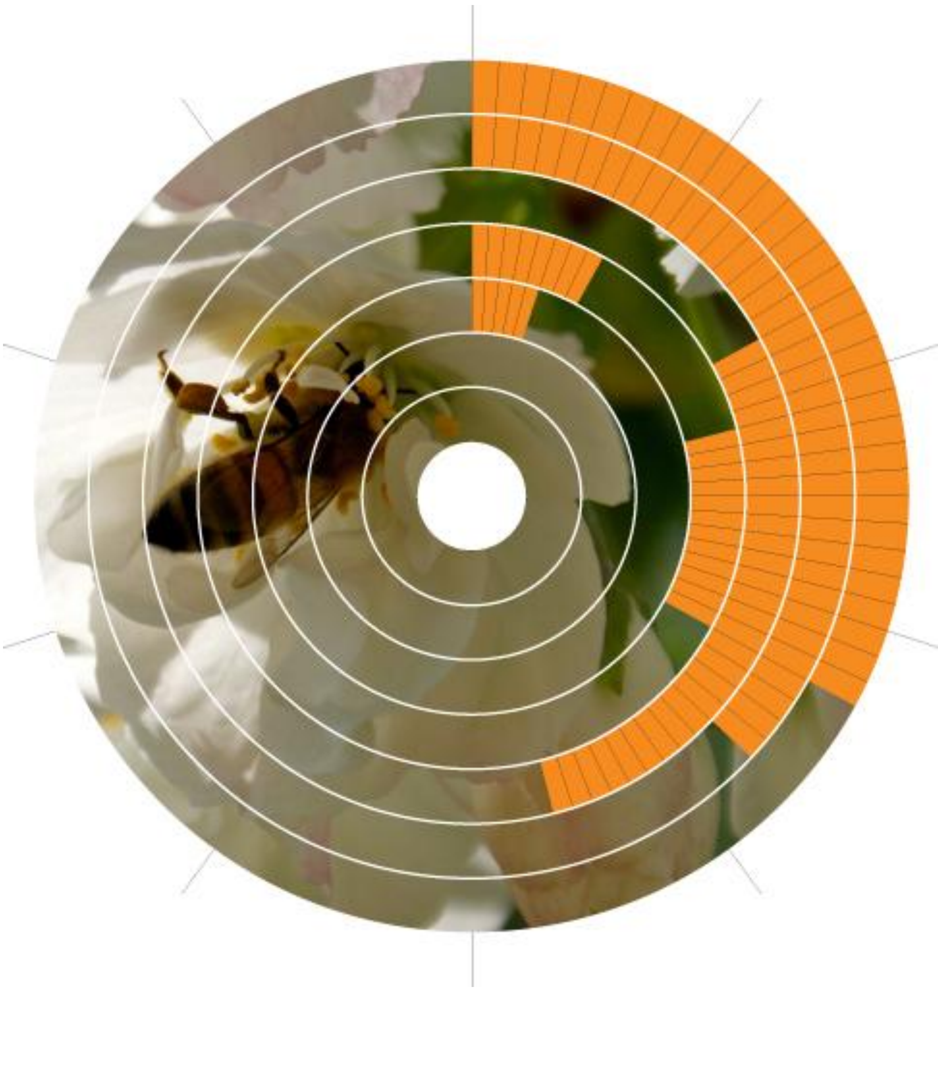

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Contents

Tables

Figures

Boxes

Summary

Australia remains the only continent free of *Varroa destructor* (referred to as 'Varroa' hereafter), a devastating mite pest of European honey bees. Varroa represents a serious potential biosecurity risk to Australia, as European honey bee colonies infested with the mite will collapse unless treatments are applied (Goodwin & Van Eaton 2001). An incursion of Varroa in Australia could be expected to seriously affect unmanaged or feral European honey bees that currently provide free pollination services to a large number of Australian crops.

In this context, the National Biosecurity Committee asked ABARES to develop a benefit–cost analysis framework that can be used in the future to assess the economic feasibility of response plans in the event of an incursion of Varroa in Australia. In responding to this request, a framework for analysis was developed and a hypothetical example of a Varroa incursion simulated to demonstrate how the model could be used in an actual event.

It must be emphasised, however, that the results presented in this paper are only illustrative of the benefits from implementing possible response plans. Information is not available on the cost and probability of successfully implementing those plans, as it will be dependent on when and where an incursion is discovered. In the event of an actual incursion, however, information on the costs and likely success of implementing particular plans would be more readily available and easily incorporated into the modelling framework to provide economic advice useful to the development of suitable response strategies.

A bio-economic model that links a spatially explicit Varroa spread module with two partial equilibrium market modules was developed. One market module covers pollination-dependent crops and the other covers the market for managed or 'paid' pollination services. Based on the experience in other countries, if there was a decline in the feral bee population it is assumed that the existing market for managed pollination services would expand to meet the increased demand for pollination services.

To demonstrate how the modelling framework could be applied, the spread module simulated the hypothetical spread of Varroa from each of the ports of Sydney, Melbourne and Cairns over a 30-year period. The market modules were then used to estimate the potential economic losses from the assumed incursion. The market modules allow the evaluation of the effect on production, prices, consumption, imports and exports of 35 pollination-dependent crops, as well as on the demand for and supply of services by the managed pollination industry. Social and environmental effects that may arise because of an incursion are not incorporated into the current framework.

Two separate spread modelling scenarios were developed for this demonstration analysis: the unhindered spread of Varroa; and the contained spread of Varroa. For each spread scenario, as shown in this study, multiple runs of the model would be undertaken to account for the uncertainty of spread. Averages of the results from these runs would then be used in the development of a response strategy.

As demonstrated for a hypothetical incursion of Varroa, the potential present value of losses to producers and consumers of pollination-dependant crops from an unhindered Varroa spread could be expected to range from $0.63 billion to $1.31 billion over 30 years depending on the port of entry (Table S1). In the scenarios examined, incursions from the ports of Sydney and Melbourne can be expected to result in higher losses than an incursion from the port of Cairns. This is because the time taken for Varroa to spread and affect the bulk of Australia's

horticultural production, which is located in the temperate regions of New South Wales and Victoria, would be longer for a Cairns incursion.

If the spread of Varroa could be slowed though containment—for example, by movement controls on managed beehives—it is estimated that the losses range from $0.36 billion to $0.93 billion over 30 years (present value), depending on the port of entry (Table S1).

Table S1 Present value of economic losses to pollination crop producers and consumers by port of entry

	Sydney	Melbourne	Cairns
	$m	$m	$m
Unhindered spread(a)	1 251	1 313	627
Contained spread (b)	825	933	355

Note: Present value calculated at a discount rate of 7 per cent

The current study's illustrative results also highlight the crucial role that an expanded managed pollination industry could potentially play in helping to reduce economic losses from an incursion of Varroa. The estimated economic losses in this study are lower than the results from some other widely reported studies. For example, Gordon and Davis (2003) estimated the sudden and complete loss of pollination services, would cost $1.7 billion a year. However, as acknowledged by these authors, this estimate did not factor in the effect of an expansion of the managed pollination services to meet increased demand. However, the scope to fully expand managed honey bee services to meet increased demand may be influenced by factors such as a current lack of skills and finance for new entrants, the increasing average age of industry members, and restrictions on hive access to public parks (DAFF 2011).

This analysis also found that a large proportion of the economic losses of crop producers and consumers would likely be in the form of payments to pollination services industries. These payments include both net income gains for pollination service providers and the additional input costs associated with expanding the pollination industry to meet high demand.

In terms of responding to a Varroa incursion, experience from countries such as New Zealand, the United States and Canada suggests it is unlikely that Varroa can be eradicated successfully. From an Australian perspective, if eradication was to be technically successful, it is generally accepted that a Varroa incursion would need to be detected early and destroyed while still near a port (Animal Health Australia 2010). If this were the case, economic losses reported for the unhindered spread scenario would represent a measure of the expected benefits of an eradication strategy. As such, the estimated benefits of eradicating a Varroa incursion range from $0.63 billion to $1.31 billion, in present value terms, depending upon the port of entry Table S2.

Table S2 Present value of potential benefits of response strategies by port of entry

	Sydney	Melbourne	Cairns
	$m	$m	$m
Eradication (a-negligible)	1 251	1 313	627
Containment (a-b)	426	380	272

Note: Present value calculated at a discount rate of 7 per cent

The contained spread scenario estimates the losses that may be incurred if the spread of Varroa could be delayed—for example, by movement controls on managed beehives. Subject to the caveats below, this response strategy is estimated to lead to lower losses than under the unhindered spread scenario. The estimated reduction in the losses (or the benefits of containment) range from $0.27 billion to $0.43 billion over 30 years, depending upon the port of entry (Table S2). This result arises because slowing the spread of Varroa reduces the production area at risk in the initial years of an incursion.

However, to determine if a response strategy (such as eradication or containment) is economically feasible, the expected benefits should be compared with the costs of implementation. The costs of implementing the response plans were not estimated in this demonstration analysis, since the costing of response plans would be contingent on the specific details of the incursion and the nature of the response. Currently, the details on how far Varroa may spread before detection are not known and cannot be reliably predicted. Nevertheless, in the event of a Varroa incursion, the benefits estimated in this hypothetical study for eradication and containment may provide a benchmark against which biosecurity decision-makers can compare the costs of implementing such plans.

It is also important to note that in this demonstration analysis, the estimated benefits for both response strategies do not take into account the probability of success of each strategy. The probability of success or likelihood of realising the estimated benefits will be lower than the 100 per cent implicitly assumed in this study. Nevertheless, the results from this study can be useful in calculating the threshold probability estimates for varying cost estimates. Such threshold probabilities may aid biosecurity decision-makers by providing the minimum success probability required for the estimated benefits of a response plan to outweigh the costs.

In practice, estimated losses may be lower if, in response to an incursion, some pollination–dependant crop producers chose to switch to alternative enterprises that do not rely on bees for pollination. However, it is difficult to estimate the size of the reduction in losses in the current modelling framework.

Finally, the modelling framework can be adapted to estimate the market impacts of a number of other pest incursions. The model can link the pest spread to datasets on agricultural production at Statistical Local Area level. To adapt the modelling framework to a different pest, the parameters of pest spread would need to be specified and the market module adjusted to represent the set of agricultural commodities that could potentially be affected by the pest.

1 Introduction

ABARES was asked by the National Biosecurity Committee (NBC) to develop a benefit–cost analysis framework to assess the economic feasibility of response plans in the event of an incursion of Varroa in Australia.

A bio-economic model was used to demonstrate how the spread of Varroa across Australia's eastern states and the resulting economic effects on pollination-dependent crops could be estimated in the event of an actual incursion. The model incorporates the effect of the development of a managed pollination industry that increases supply of pollination services in response to increasing demand. The model also produces estimates of the potential effect of Varroa on the production of honey bee pollination–dependent crops, as well as the benefits of response plans involving eradication or containment.

Background information on the honey bee industry in Australia and the international experiences of reported Varroa incursions are discussed in chapter 2. The modelling approach used to estimate the benefits of implementing response plans are summarised in chapter 3. The scenarios examined in the modelling framework are outlined in chapter 4. The parameter data and assumptions used and their sources are outlined in chapter 5. Finally, illustrative estimates of the benefits of eradication and containment response plans to hypothetical Varroa incursions from the ports of Sydney, Melbourne and Cairns are presented in chapter 6.

2 Background

Australia is currently free of Varroa, a devastating pest of European honey bees. Varroa feeds on larvae, pupae and adult bees, causing weight losses, aiding viral infestations and finally causing death (Goodwin & Van Eaton 2001). Colonies infested with Varroa collapse within two to three years (Keogh, Robinson & Mullins 2010), although they can collapse in a number of months under some environmental conditions (DAFF 2011).

Until 1999, Varroa had been reported in most beekeeping areas of the world with the exception of Australia and New Zealand. The threat of a Varroa incursion in Australia has been heightened since the pest became established in New Zealand in 2000. It is generally accepted as more than likely that Varroa will enter and become established in Australia (Keogh, Robinson & Mullins 2010). The impact on the honey and pollination industries following the discovery of Varroa in Canada, the United States and New Zealand is set out in box 1.

The Australian honey bee industry is built around colonies of European honey bees, with about 10 500 registered beekeepers operating approximately 542 900 hives (R Goodman [Victoria DPI] 2011, pers. comm., 8 February). In 2009–10, Australian honey and beeswax production was valued at $55.4 million and queen bee exports at $0.4 million (ABARES unpublished). As well as managed honey bees, Australia also has a large population of feral European honey bees due to favourable climatic conditions and nectar-rich native flora (Cook et al*.* 2007).

Honey bees, both managed and feral, contribute to crop production by providing pollination services to many horticultural crops, as well as a few broadacre crops. In 1999–2000, the value of the pollination services from honey bees in Australia, in terms of the cost of a sudden and complete loss of pollination services, was estimated to be about $1.7 billion a year for 35 crops dependent on honey bee pollination (Gordon & Davis 2003). Despite this significant reliance of crops on pollination, it is estimated that only around 28 per cent of honey bee businesses provide pollination services for a fee (Crooks 2008). Therefore, incidental pollination from bees managed for honey production and from feral bees is important for crops.

It is likely that in the event of a Varroa incursion, Australia's feral bee population will be largely eliminated (DAFF 2011). Untreated colonies experience a rapid reduction in health and ultimately mortality. In New Zealand, it has been estimated that Varroa reduced the number of feral colonies by about 99 per cent (Goodwin, Scarrow & Taylor 2006), which is similar to the estimated 95 to 98 per cent loss of feral colonies in the United States (Cornell University 1997).

Internationally, commercial beekeepers have generally been able to use well-developed management techniques to avoid losing colonies to Varroa, albeit at increased costs (Goodwin & Van Eaton 2001). The cost of managing hives increases because of additional labour and chemical input requirements (Biosecurity New Zealand 2002; MAF 2008). In New Zealand, the additional management cost of treatment per hive is estimated to range from NZ$40 to NZ$55 a year (MAF 2001, 2010).

Box 1 Honey and pollination in the United States, Canada and New Zealand

United States

Since the discovery of the Tracheal mite (in 1984) and Varroa (in 1987), the number of hives producing honey and honey production in the United States have declined (National Research Council 2007; USDA 2011). The number of colonies managed by beekeepers declined from 4.2 million in 1981 to 2.5 million in 2005. Domestic production of honey in the United States fell during the same period despite a 50 per cent increase in the yield of honey per hive (Ward & Boynton 2010). Information on colonies exclusively providing pollination services is unavailable since the annual government honey surveys only consider colonies from which commercial honey is harvested (National Research Council 2007).

As observed by Daberkow, Korb and Hoff (2009), the structure of the US honey bee industry is undergoing a significant structural change, with a shift from honey production to pollination service provision. Between 1982 and 2002, there was a 70 per cent decline in the number of beekeepers, with a large number of those exiting operators accounting for a small proportion of hive numbers. Over this same period, the number of commercial beekeepers increased, with those managing more than 1000 hives accounting for nearly half of all hives (Daberkow, Korb & Hoff 2009).

Although less than 1 per cent of beekeepers in the United States are commercial operators (National Research Council 2007), they operate more than 2 million hives (Johnson 2007) and account for around 99 per cent of all pollination rentals (Burgett 2004). Each February, about two-thirds of the nation's honey bee hives are placed in California's almond orchards for pollination (USDA 2011). While almond producers have reportedly 'continued to produce big crops in most years', there have been increases in renting costs of colonies (USDA 2011). These increases in costs have been driven by supply and demand for pollination services. On the supply side, hive losses of between 15 and 30 per cent—as a result of adverse weather conditions, several pests and diseases (including, Varroa, Nosema, small hive beetle and American foulbrood) and the impact of colony collapse disorder (USDA 2010)—have reduced the number of available hives. On the demand side, there has been an increase in the demand for hives with increased plantings of pollinator-dependent crops (National Research Council 2007; USDA 2011) such as almonds in California (James and Pitts-Singer 2008). The increase in the cost of hiring hives has helped to promote the use of alternative pollinators.

Canada

Since the discovery of Varroa in 1989, Canada has witnessed a dramatic change in the structure of the beekeeping industry, from one dominated by part-time hobby operations to one with a substantial number of full-time commercial beekeepers. There has also been an increase in average honey production per colony (Melhim et al. 2010), which may have been driven by the exit of many hobby beekeepers and improved hive management since the arrival of Varroa (Goodwin & Van Eaton 2001).

After the initial incursion there was a large decline in colony numbers, falling from 700 000 to around 500 000 colonies in the 1990s (Melhim et al. 2010). Over the past decade, however, colony numbers have steadily increased to around 600 000. This increase in colony numbers is despite reported increases in hive mortality rates, with winter losses doubling from 5–15 per cent in 1992 to around 35 per cent between 2007 and 2009 (Currie, Pernal & Guzmán-Novoa 2010; Melhim et al. 2010). While Varroa has been identified as the main cause of the increased mortality, unusual weather and other parasites have also been recognised as contributing to these losses (Currie, Pernal & Guzmán-Novoa 2010).

Honey bee pollination has become increasingly important in Canada due to the fast growth of pollination-dependent crop production of fruits, berries and seeds (Melhim et al. 2010). Even with the presence of Varroa, Canada's increasing pollination needs have been met largely by managed honey bee colonies, with pollination by managed non-*apis* pollinators meeting residual pollination service needs (Melhim et al. 2010).

New Zealand

Following the discovery of Varroa in 2000, there has been a large decline in the number of beekeepers. Between 2000 and 2007, the number of beekeepers fell by 47 per cent. This decline was driven mainly by the exit of both hobby beekeepers and the high-cost honey producers whose operations became unprofitable as a result of the increase in hive treatment costs (MAF 2010). Although there was an exit of a large number of hobbyist beekeepers, the aggregate number of hives fell by just 2 per cent (MAF 2007).

High prices for Manuka honey and revenue from pollination and live bee exports have helped the New Zealand beekeeping industry remain profitable in the face of increases in hive management costs and additional hive losses due to Varroa (MAF 2010). While the presence of Varroa initially restricted bee exports to Canada, Japan and the United Kingdom (MAF 2001), bee exports to Canada and the UK have resumed (MAF 2007), with record exports to Canada in 2009 (MAF 2010). The combined effect of a high price of honey and a decline in pollination services from feral honey bees due to Varroa have increased demand for managed hives both for pollination services and for honey production.

Since 2006 there has been a steady increase in the number of managed colonies, reaching a high of 375 000 hives in 2010. Since 2010, there have also been increases in the number of registered beekeepers—anecdotally this has been due to hobby beekeepers interested in food production servicing a niche market, as well as new entrants to commercial beekeeping attracted by the high Manuka honey prices (MAF 2010).

Australia has a large proportion of small-scale beekeepers. Crooks (2008) estimated that 83 per cent of Australian beekeepers operated fewer than 50 hives each and managed 10 per cent of the total number of hives. Based on overseas experience, a Varroa incursion in Australia would be expected to result in a large restructure and commercialisation of the honey bee industry in response to increasing demand for pollination services.

The experience in New Zealand and Canada, for example, was that beekeepers unable to absorb the additional cost of hive management, such as hobby beekeepers and honey producers with low profit margins, exited the industry (MAF 2010). Despite the fall in the number of beekeepers in these countries, colony numbers and honey production increased as a result of the increased commercialisation of the honey beekeeping industry (Goodwin & Van Eaton 2001; Melhim et al. 2010). In effect, the incursion of Varroa required beekeepers to improve overall beekeeping management and to become more efficient (Goodwin & Van Eaton 2001).

However, some recent reports have highlighted that a number of factors could limit the managed honey bee industry's ability to increase hive supply in Australia. These factors include: a lack of skills and finance for new entrants; increasing age of industry members; other pests and diseases; and potentially reduced access to native flowering vegetation because of drought and government restrictions on accessing public parks (DAFF 2011).

Many beekeepers, particularly those with a small number of hives, derive recreational benefits from managing hives in addition to the financial benefits from selling and consuming bee products. If they were forced to exit the industry as a result of additional hive treatment costs, they would lose these recreational benefits. Since the Australian honey bee industry has a large proportion of small-scale or amateur beekeepers, the associated loss of recreational benefits following a Varroa incursion would be expected to be significant. However, these losses are difficult to quantify and have not been examined in the current analysis.

The environmental impacts of a Varroa incursion have also not been included in this study because of difficulties in quantifying those impacts and the fact that Varroa affects European honey bee which is an introduced species to Australian environment. It may be questionable that apparent environmental impacts of the elimination of an introduced species could be treated in the same way as the environmental impacts of the elimination of a native species. However, there has been a number of studies that looked at the environmental effects of reduced European honey bee populations.

Reduced numbers of introduced European honey bees could affect ecosystems services in a number of ways. However, the limited available literature suggests there are contradictory effects, with differing conclusions about the effects on native pollinators (Gordon & Davis 2003; Paini 2004; Paton 1996); seed setting of native flora (Paton 1993, 1996) and invasive weeds (Goulson & Derwent 2004; Simpson, Gross & Silberbauer 2005); and the availability of tree hollows for native species (DECC 2002; Paton 1996). The apparent environmental impacts of reduced honey bee colonies remain, at best, ambiguous.

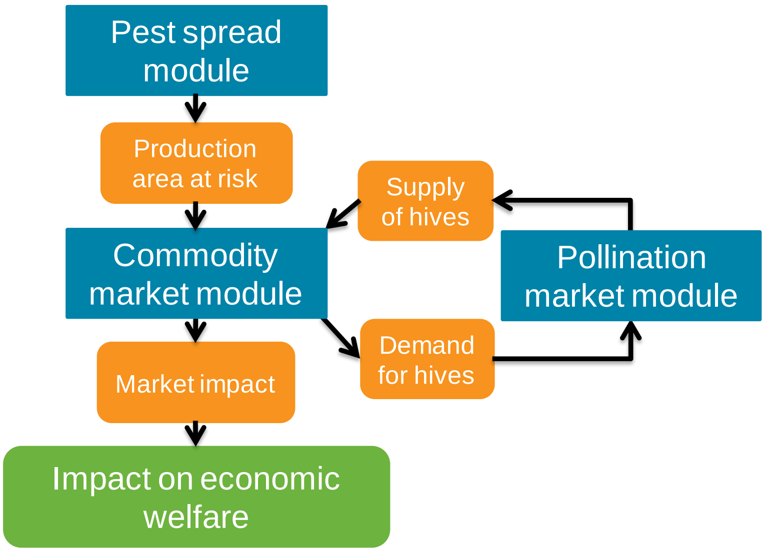
In addition, while literature examining Australia's 1500 native bee species is scarce, it is considered highly unlikely that they would be adversely affected by Varroa. This is because the reproduction and survival of Varroa is highly dependent on the timing of the European honey bee's life cycle, which is significantly different to that of both solitary and more social native bees.

3 Modelling approach

In this chapter, the modelling framework that may be used to assess the economic effect on Australia of an incursion of Varroa is summarised. Building on the approaches taken by Gordon and Davis (2003), Cook et al. (2007) and Monck et al. (2008), the bio-economic model developed is designed to evaluate the impacts on economic welfare by combining the spread of Varroa with the impacts on commodity markets (see appendixes B and C for technical details). As illustrated in figure 1, this model integrates three separate modules:

- Varroa spread module, which simulates the temporal and spatial spread of the pest across eastern Australia
- partial equilibrium module of the markets for pollination-dependent crop products
- partial equilibrium module of the markets for pollination services.

Figure 1 Process for modelling the impact of Varroa



The spread of Varroa and consequent losses in economic welfare are measured over a 30-year period; a discount rate of 7 per cent is applied in calculating the present value based on advice from the Office of Best Practice Regulation of the Department of Finance and Deregulations (Australian Government 2010). The benefits, in terms of avoided economic welfare losses, of two response strategies (eradication and containment) are estimated. Further details on the two spread scenarios and response strategies are given in chapter 4.

Varroa spread module

The spread module simulates the spread of Varroa using a grid of 5 kilometre by 5 kilometre cells across eastern Australia. It is assumed that Varroa spreads within feral honey bee populations, from feral honey bees to commercial hives, within commercial enterprises, and from commercial enterprises back to feral honey bees. It should be noted that the spread of Varroa arising from trade in hives and queen breeders are not represented. The likelihood of spread of Varroa via trading of hives and queen breeders is likely to be negligible relative to spread of Varroa via movement of hives for the purpose of providing pollination services. A brief discussion of this module is outlined below; however, a technical summary is presented in appendix B.

The spatial distribution of feral honey bee colonies was generated using a habitat suitability map based on annual rainfall and maximum summer temperatures. Parameter values used in generating this distribution were tuned so that the resulting dispersion of feral honey bee colonies broadly matched that described by Technical Working Group members. The geographical distribution of managed hives by Statistical Local Area (SLA) was generated using the findings of a survey of beekeepers by Bresolin and Peterson (2010). Following Crooks (2008), it is assumed that there are 1700 beekeepers distributed across eastern Australia and that in each year they worked their hives over an average of approximately seven sites.

The spread of Varroa was simulated separately for incursions through the ports of Sydney, Melbourne and Cairns. These ports are considered to be the most likely entry points given the large volume of trade through the ports of Sydney and Melbourne and the fact that Asian honey bee (*Apis cerana*) entered through the port of Cairns.

Interactions between feral and managed hives are assumed to result in Varroa spreading by two means. First, normal foraging activities of honey bees is assumed to result in natural diffusion spread of Varroa across Australia. Parameters governing this process were tuned to give an average spread rate of approximately one kilometre per month over the first 18 months of the incursion, based on the findings of Stevenson et al. (2005). Second, the movements by beekeepers are assumed to enable the spread of Varroa over longer distances. Moving infested hives for pollination services and for honey production (limited to within 650 kilometres from the apiary home site) allows long-distance jumps in the spread of Varroa.

The spread module simulates the spread of Varroa at monthly time steps over 360 months (or 30 years). The spread and density of Varroa is calculated for each SLA, at each time step, identifying new SLAs where Varroa has entered while updating the pest density of those SLAs where Varroa has already established, to account for both the spread and growth in pest population during that time step. For each time step and SLA, the proportion of the production of pollination-dependent crops at risk is assumed to be equal to the density of Varroa, which is scaled to range from 0 to 1. This simplifying assumption enables the linking of the spread module to the pollination market module and the commodity market module for the pollination-dependent crop products.

Pollination market module

This module incorporates a simple market module of supply and demand for pollination services at an aggregate level. A brief discussion of this module is presented below, and a technical summary is presented in appendix C.

The equilibrium price of hives for pollination services is solved by equating the aggregate demand for hives to the aggregate supply of hives. The quantity of hives demanded is equal to the profit maximising level of use of hired pollination inputs in the production process. This quantity is determined as the point at which the value of marginal product of pollination provided by a hired hive equals the market price of hives. The aggregate supply of hives is modelled as a constant elasticity function of the market price of hives.

A market for paid pollination services currently exists and is being used primarily by the almond and cherry industries. As pollination-dependent crop producers are assumed to substitute hired pollination services for the loss of feral honey bee pollination services, the aggregate demand for hired pollination services is expected to increase.

The increase in demand for pollination services is equal to the aggregate number of additional hives required to replace the pollination services provided by feral hives. For each year and crop, the number of hired bee hives required to replace the services of the lost feral bee hives is estimated as the product of the pollination-dependent production at risk—as estimated using the results of the pest spread module—and the number of hired hives used per tonne of product. The sum of additional hives required for all crops equals the increase in aggregate demand. As the aggregate demand increases, this module solves for the new equilibrium price of hives by equating the demand and supply of hives. The resulting higher price of hive rentals causes an increase in the marginal cost of crop production, which is then used to link the pollination market module to the commodity market module through the response of pollination-dependent crop producers.

Commodity markets module

This module is built around the interaction between supply and demand for pollination-dependent crop products. A brief discussion of this module is presented below, and a technical summary is presented in appendix C.

On the supply side, the model includes domestic and import supplies; on the demand side, it includes domestic and export demands. The equilibrium price in the domestic market is solved by equating domestic supply to domestic and export demands.

Producers supply both domestic and export markets, while consumer demand is met by both domestically produced and imported products. The domestically produced and imported products are treated as imperfect substitutes, with the rate of substitution being determined by the elasticity of substitution assumed (Armington 1969). Export demand responds to domestic price, while domestic demand responds to share weighted domestic and import prices of the same product. It is assumed that Australia is a price taker and therefore any change in Australian production has no effect on the world price of the products.

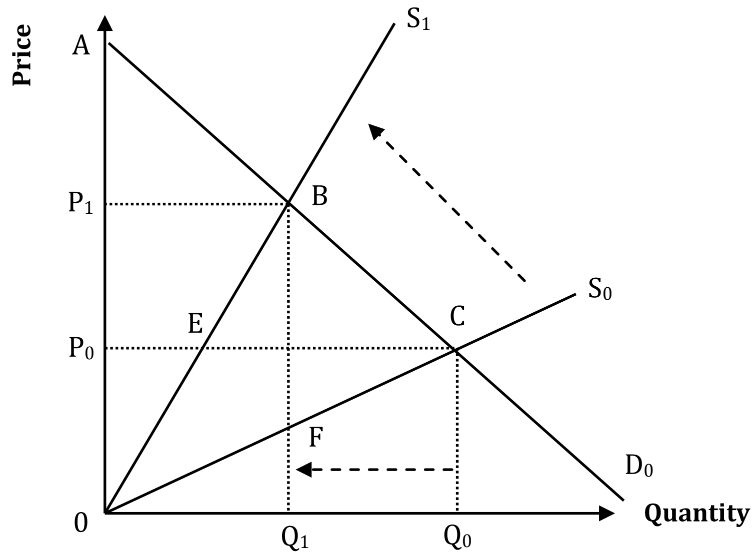
The impact of Varroa spread on the commodity markets is determined by the increase in the marginal cost of production, illustrated by a pivotal shift in the supply curve. These shifts result in changes in producer and consumer economic welfare, as discussed below.

Estimating economic losses

The increase in the price of hired pollination services—as estimated in the pollination market module—will increase the cost of production for crop producers, pivotally shifting the supply curve for each crop in the commodity market module. The total economic losses arising from the shifts in supply are estimated as the sum of the losses in producer and consumer surpluses for all crops.

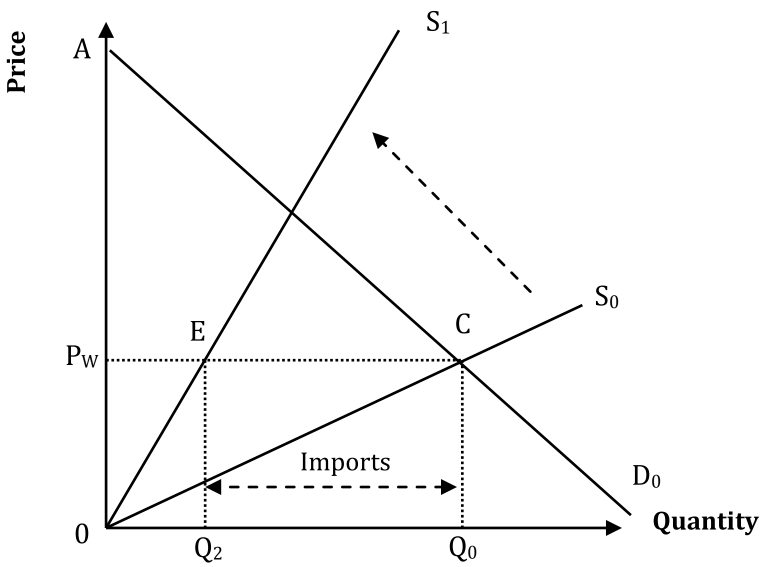
The measurement of the losses in consumer and producer surpluses for a given commodity is illustrated in figure 2 using a simple supply and demand model (assuming no import substitution). The increased production cost from Varroa is depicted by the pivotal shift in the supply curve from OS_0 to OS_1. The increase in production cost causes crop producers to cut back production from Q_0 to Q_1, leading to an increase in the price of product from P_0 to P_1. The loss in consumer surplus, due to higher cost of consuming a product and reduced consumption, is represented by the area P_1BCP_0. The loss in producer surplus is equal to the area OEC-P_1BEP_0. The total loss in economic welfare is equal to the change in total surplus, represented by the area *BCO*. Of this, the area *OBF* measures the increase in payments to pollination and allied support services industries from producers and consumers of pollination-dependent crop products (for example, transport and logistics).

Figure 2 Changes in economic surplus without import substitution



The overall loss in consumer surplus is partially dependent on the scope for consumers to substitute other goods, especially imports. If imports are perfectly substitutable for domestic products, both price and domestic consumption remain constant at P_W (the world price) and Q_0 in figure 3; however, domestic production declines to Q_2 and imports would be Q_0-Q_2. Hence, the loss in economic welfare is equal to the area *0EC*—where consumer surplus is unchanged and the loss in producer surplus accounts for all of the loss in economic welfare. Alternatively, if imports are not perfectly substitutable for domestic goods, as is assumed in this study, then the losses in economic welfare, and its components, are similar to those displayed in figure 2.

Figure 3 Changes in economic surplus with perfect import substitution



In the context of these figures, a successful eradication of Varroa would enable the supply curve to move back to S_0. This limits the economic welfare losses described above to those losses, if any, incurred between the dates of incursion and successful eradication. A control strategy is designed to slow the movement of the supply curve from S_0 to S_1 by slowing the spread and impact of Varroa. A control strategy therefore results in smaller production and economic welfare losses initially, relative to unhindered spread, until the pest eventually reaches the saturation point when the loss will be the same under both scenarios.

4 Scenarios examined

To demonstrate how the modelling framework for a Varroa incursion could be applied, two hypothetical spread scenarios were developed. The two scenarios are an unhindered spread scenario and a contained spread scenario. This chapter contains specific details on the assumptions underlying the spread modelling scenarios as well as an explanation of how the economic losses and the benefits arising from response strategies are defined and estimated.

Unhindered spread

The unhindered spread scenario assumes that there is no coordinated response by government or industry to control or eradicate an incursion. Under this scenario, Varroa is expected to spread over short distances by natural diffusion (as managed and feral bees travel around their home colonies) and over longer distances as managed colonies are transported by beekeepers.

Contained spread

The contained spread scenario assumes that a response strategy is adopted to try to slow the spread of Varroa. It is assumed that the government enforces movement restrictions and that affected beekeepers comply with them fully. Movement restrictions are applied sequentially to:

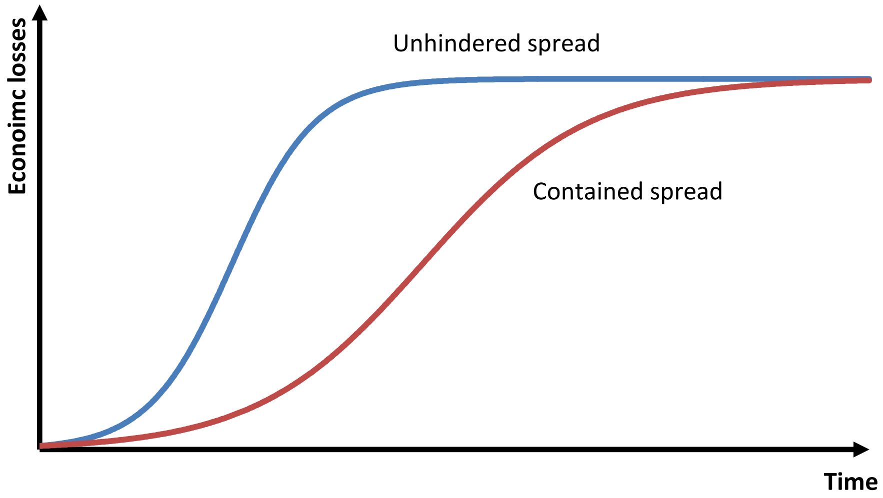
- a restricted area (buffer zone) of 50 kilometre radius around the port of incursion (movement restrictions are assumed to prevent hives being transported out of the buffer zone)
- the transportation of hives across state borders for those states where an incursion is assumed to occur (these movement restrictions apply once Varroa has breached the buffer zone).

The assumptions underlying these scenarios are broadly consistent with international experiences in responding to a Varroa incursion (box 2), as well as the AUSVETPLAN Disease Strategy: Bee diseases and pests (Animal Health Australia 2010). In particular, the AUSVETPLAN states that 'state/territory and/or industry-based control measures will be initiated. This may include interstate movement controls and encouraging industry to develop its own long-term policies and procedures'. As noted by DAFF (2011), since interstate movement of bees currently requires a health certificate, control areas could be established to prevent interstate movement. Alternative control strategies such as a national standstill or 'creeping' controlled area have not been considered in this analysis.

Economic losses from different spread rates

Figure 4 represents a schematic depiction of economic losses over time for the unhindered and contained spread scenarios. The shape of the economic losses curve mirrors the establishment, expansion and saturation stages of a Varroa incursion. The slower pest spread in the contained spread scenario results in lower losses in the early years, before reaching the maximum loss as in the unhindered spread scenario. Hence, the aim of containment can be thought of as slowing the spread of Varroa to give industry time to adjust to the eventual saturation of Varroa.

Figure 4 Economic losses over time from different spread rates of Varroa



In estimating the economic losses, it is assumed that beekeepers adopt hive treatment measures and growers of pollination-dependent crops substitute hired pollination services for lost feral honey bee pollination. Economic effects for the unhindered and contained spread scenarios are estimated using the results from the spread module.

Box 2 Biosecurity policy responses to Varroa incursions in other countries

The experience of the United States, Canada and New Zealand in relation to their biosecurity responses to a Varroa incursion are summarised below.

United States

Varroa was first detected in late September 1987 (Goodwin, Scarrow & Taylor 2006) as a result of tests on hives that experienced sudden declines in colony size during transport from Florida to Wisconsin. A nationwide survey revealed the presence of Varroa across the US mainland, in the states of Maine, New York, Rhode Island, Pennsylvania, Ohio, Michigan, South Dakota, Nebraska, Illinois, Wisconsin, Florida and Mississippi. As a result, plans developed earlier to restrict interstate movements as part of a containment and eradication program were never implemented. By 1995, Varroa was widespread, assisted by the distribution of queen and package bees, as well as the movement of colonies by beekeepers for pollination and over-wintering (Wenner & Bushing 1996).

Import restrictions on honey bees and beekeeping equipment allowed the state of Hawaii to remain free of Varroa until 2007, when it was detected on the island of Oahu. Initially, stamping out of infested hives was undertaken; however, surveys indicated that Varroa was widespread and likely to have already been present for about a year. As a result, eradication was deemed infeasible.

Instead, inter-island quarantine and bee-free buffers were set up around airports and harbours to limit the spread across the Hawaiian Islands. However, by August 2008 Varroa was discovered on the main island (Hawaii Island). Following this discovery, an attempt was made to destroy all feral hives within a five-mile zone. Bait traps were deployed in January 2009, but delays in gaining regulatory approval for the traps reduced their effectiveness. Following the movement of managed hives out of the containment area and the resulting wide distribution of Varroa, eradication was deemed to be no longer feasible on Hawaii Island (Department of Agriculture State of Hawaii 2009).

Canada

Isolated cases of Varroa were first detected in New Brunswick in 1989, near the US border. Initially, an eradication strategy was adopted with mandated testing, quarantining and destruction of infested colonies (Clay 1996). Two zones were established around infestations: a primary zone (8 kilometre radius) and a secondary zone (24 kilometre radius). All feral honey bee hives within the primary zone were destroyed, while in both zones the movement of managed colonies was only permitted under licence (Agriculture Canada 1992).

Several other policies were adopted to combat the spread of Varroa, including bans on imports of packaged and queen bees from the United States; bans on imports of honey bees from countries other than New Zealand and

Australia by a number of provinces; and adoption of voluntary movement restrictions by beekeeper associations. A number of provinces allowed imports of honey bee hives once a health certificate had been validated; however, this policy encountered several problems. Namely, the health certificate validation was not undertaken immediately prior to movements, allowing Varroa to infest cleared hives. Additionally, systematic tracking of hives was not adopted, making tracing difficult (Clay 2002).

By mid-1992, Varroa had been discovered in the provinces of Ontario, Quebec and Manitoba. As a result of increasing compensation and surveying costs, it was decided to continue to pursue eradication but without compensation, under the National Varroa Action Plan (Clay 2002). However, by the end of 1992, it was decided to not continue destroying infested hives, partly because of pressure from beekeepers. By 2002, Varroa was present in most beekeeping regions (Currie, Pernal & Guzmán-Novoa 2010).

New Zealand

The initial discovery of Varroa in New Zealand, outside Auckland in April 2000, led to a survey of apiaries in the upper North Island lasting seven weeks. This survey revealed that on average 10 per cent of apiaries were infested with Varroa, with a high number of infested hives within a 7 kilometre area surrounding Auckland International Airport (Biosecurity New Zealand 2001). These results, and the density of infestation, suggested that Varroa had been present in New Zealand for three to four years.

The cost of eradicating Varroa from the North Island was estimated at NZ$ 55 million with an associated low probability of success (New Zealand Audit Office 2002). The decision was made to adopt a management strategy with movement controls rather than to attempt eradication. A number of additional factors were taken into account in supporting this decision, including low reliability of the testing procedure for detecting new infestations; low success rate for eradicating Varroa from the feral honey bee population; and public concerns over environmental and health impacts.

In June 2006, Varroa was first discovered in the South Island, outside Nelson. A survey revealed a number of infested sites, most within 10 kilometres of Nelson (MAF 2006). The cost of eradication from the South Island was estimated at between NZ$8 million and NZ$9 million with an 80 to 85 per cent probability of success (Somerville 2008). However, a decision was made not to pursue eradication, because of factors such as a strong likelihood of re-incursion from the North Island; legal issues with the chemicals identified to destroy feral honey bees; and the terrain around Nelson making it difficult to find and destroy feral bee colonies.

Zones restricting the movement of hives and beekeeping equipment were established on both the North Island and South Island to limit long-distance jumps in the spread of Varroa. The zones were gradually shifted as Varroa became established in new regions. The movement controls, surveillance and research activities were designed to ensure unaffected parts of the country remained free of Varroa for as long as practicable and to mitigate the impact of Varroa in infested areas. The response program ceased in June 2009 after Varroa was found in a large number of beekeeping operations outside the controlled area.

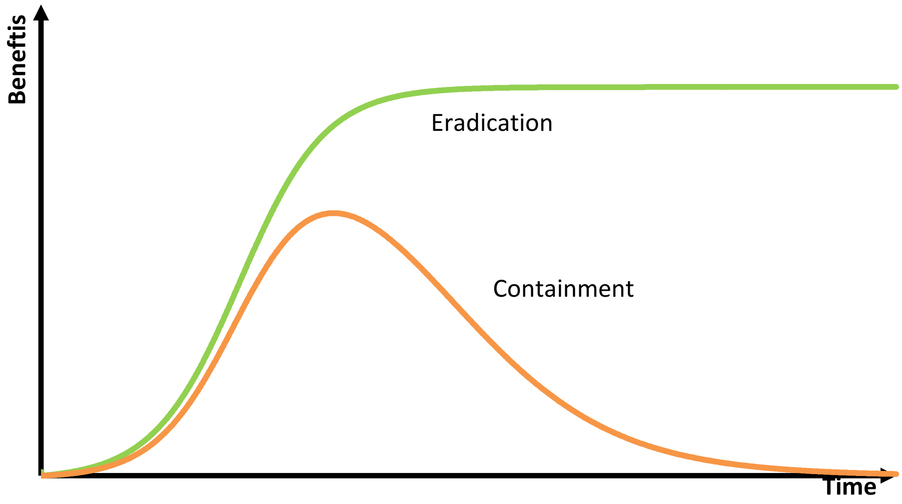
Benefits of response strategies

The benefits over time of adopting a response strategy to a Varroa incursion are represented by the difference between the economic losses if it is not implemented and the economic losses if the strategy is implemented. In other words, the estimated benefits of the response strategies are estimated economic losses that are avoided as a result of implementing a response strategy.

A spread scenario for eradication of Varroa has not been explicitly modelled. This is because it is assumed that Varroa is detected and eradicated early before it is able to spread and affect honey bee pollination services. This is broadly consistent with the *AUSVETPLAN Disease Strategy: Bee diseases and pests*. The AUSVETPLAN suggests that eradication would only be carried out if a number of conditions were met. These are: that Varroa is not present over multiple sites (usually two to three sites); that Varroa is not considered to be established; and that Varroa has not spread out of the surveillance zone (about a 10 kilometre radius).

In other words, the benefits for eradication are assumed to be equal to the economic loss under unhindered spread. The benefits increase over time to a maximum loss reflecting the saturation stage of Varroa (figure 5).

Figure 5 Benefits of implementing response strategies over time



In the case of the containment response strategy, the benefits are the differences between the economic losses under unhindered spread and under contained spread. The benefits of containment initially increase to a maximum but subsequently decline to a negligible level because the economic losses under the contained spread scenario converge to the maximum loss under the unhindered spread scenario.

5 Data and assumptions

Data on the scientific and economic parameters gathered from various sources were used in the model. These include parameter assumptions on the spread of Varroa, on pollination-dependent crops and on the pollination services industry.

Pollination-dependent cropping industries

Similar to earlier studies, 35 honey bee pollination–dependent crops were selected to comprehensively account for the impact of reduced pollination services on agricultural industries. Most of the crops selected have a high dependence on honey bee pollination (table 1). Crops such as asparagus, beans, broccoli, brussel sprouts, cabbage, carrot, cauliflower, celery, lettuce and onion, which are reliant on pollination for seed production, have been included under 'Vegetable seed'.

If both managed and feral honey bee pollination services were to cease, the production of a given crop would be reduced by the relevant percentage in table 1. The remaining production is sustained by the pollination services provided by other pollinators. For example, without honey bee pollination services avocado production would decline by 90 per cent. If pollination is currently carried out by feral bees, which are lost with an incursion of Varroa, this dependence on honey bee pollination determines the number of hired hives required to maintain production. It is recognised that with monoculture planting, honey bee pollination dependence varies between locations; however, because of data limitations, these differences have not been incorporated in the model.

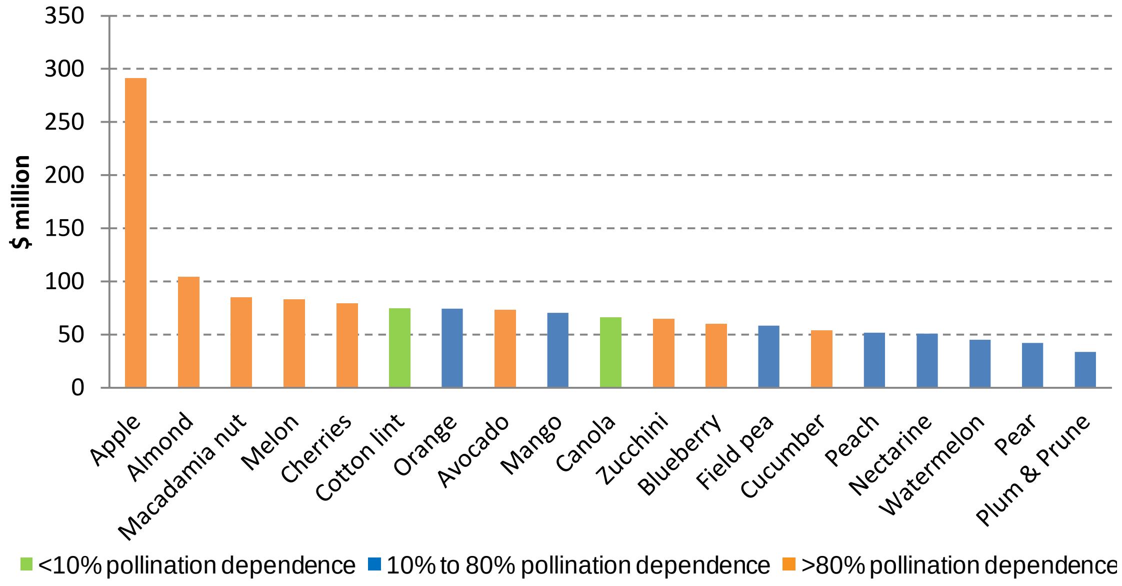
Table 1 Percentage of production dependent on honey bee pollination

Crop	Dependence (%)	Crop	Dependence (%)	Crop	Dependence (%)
Almond	100	Grapefruit	72	Peanut	2
Apple	81	Kiwifruit	72	Pear	45
Apricot	56	Lemon & Lime	18	Plum & Prune	63
Avocado	90	Lucerne seeds	90	Pumpkin	10
Bean—soybeans	5	Lupin	10	Raspberry	90
Blueberry	90	Macadamia nut	81	Rockmelon	90
Canola seed	90	Mandarin	27	Strawberry	4
Canola	14	Mango	72	Sunflower	90
Cherries	81	Nectarine	48	Watermelon	63
Cotton lint	8	Orange	27	Zucchini	90
Cucumber	90	Papaya	16	Vegetable seed	90
Field pea	45	Peach	48		

Sources: ABARES calculations based on Cook et al. (2007); Cunningham, FitzGibbon and Heard (2002); Gordon and Davis (2003); Keogh, Robinson and Mullins (2010); Monck, Gordon and Hanslow (2008); and Morse and Calderone (2000).

Based on the Agricultural Census 2005–06, the aggregate gross value of production of the pollination-dependent crops is estimated to be $4.3 billion, while the gross value of honey bee pollination–dependent production (the product of honey bee pollination dependence and value of production) is estimated at $1.6 billion for the same year. The gross value of honey bee pollination–dependent production for the top 20 crops is shown in figure 6. It shows that apples, almonds, macadamia nuts, melons and cherries have a very high degree of honey bee pollination dependence.

Figure 6 Value of pollination-dependent production for top 20 crops: Australia



Note: Value of production dependent on honey bee pollination is the product of annual crop value and the percentage of crop dependent on honey bee pollination.

The market module requires data on base-year production, consumption, import and export quantities and domestic and export prices for each pollination-dependent crop. Data on the quantity of imports and exports for each crop in 2005–06 were sourced from the Australian Bureau of Statistics (2010) and the unit prices of imports and exports were derived by dividing the value of imports and exports by respective quantities. Data on aggregate quantity and value of production were obtained from the Agricultural Census of 2005–06 (Australian Bureau of Statistics 2008a, 2008b) and was supplemented with levy data on lucernes and clovers seed production. The domestic unit price of the 35 crop products was obtained by dividing the gross value by the quantity produced. The consumption of domestically produced products is derived as the difference between domestic production and exports.

The Agricultural Census 2005–06 was used to provide a breakdown of the quantity and value of pollination-dependent crops produced at the SLA level. These data, along with the data on percentage of honey bee pollination dependence and the results of the spread modelling, were used to estimate the potential reduction in production at the SLA level.

The data on supply and demand elasticities used have been adapted, with some adjustments, from Gordon and Davis (2003). For the elasticity of substitution of imported products for domestically produced products, an elasticity value of either 3 or 10 is used. For example, almonds are assumed to have an elasticity of 10, implying a high degree of substitutability of imported almonds for domestically produced product. Current import restrictions allow almonds to be imported from all countries conditional on an import permit and after being subjected to meeting biosecurity requirements (AQIS 2010). Appendix D provides base-year aggregate production, consumption, imports, exports and prices, as well as elasticities used to calibrate the commodity market module.

Pollination services industry

The pollination market module is calibrated to reflect the current pollination industry situation. Following Monck et al. (2008), it is assumed that currently there are 200 000 hives providing pollination services at an average price of $80 per hive. As the feral bee population declines, it is assumed that affected industries substitute paid honey bee pollination services for the lost feral bee pollination services. As estimated by Monck et al. (2008), demand for pollination hives is expected to increase to 430 000 units, placing upward pressure on the price of hive rentals.

A recent assessment of supply constraints on the Australian managed pollination industry by Ryan (2011) found that the industry would not be able to expand the supply of pollination services to meet increased demand as a result of a Varroa incursion while also maintaining its current focus on producing both honey and pollination services. However, in the event of a Varroa incursion, it was expected that increased demand for pollination services could attract new entrants and support the emergence of a specialised pollination services industry. Ryan (2011) estimates that hive rentals would need to increase to $436—$473 per hive for a specialised pollination industry to be economically viable.

This assessment was incorporated in the pollination market module by choosing parameter values to allow the price of hives to increase to the above levels following a Varroa incursion. The higher price for rental of hives in the pollination market module also includes an increase in hive management cost of $50 per hive (Biosecurity New Zealand 2002) in those regions affected by Varroa.

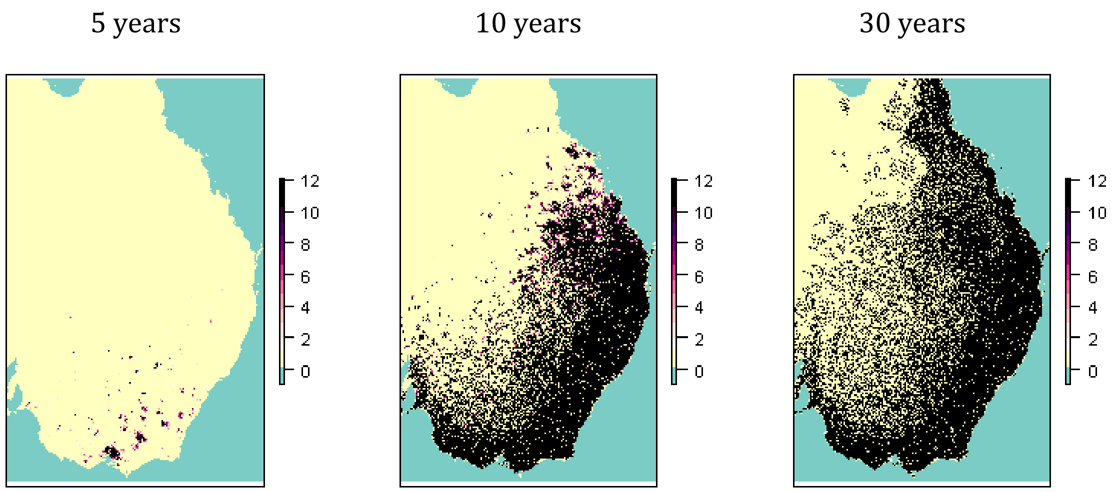
6 Modelling results

This chapter contains estimates of the spread and economic modelling results for a hypothetical incursion of Varroa. Estimates for the benefits of illustrative eradication and containment response strategies for incursions originating from the ports of Sydney, Melbourne and Cairns are also provided. A number of caveats in interpreting the estimated economic losses and benefits are also detailed. The sensitivity of the results to changes in the assumed honey bee pollination dependence of crops and discount rate is also examined. Finally, some evaluation tools are outlined to assist biosecurity decision-makers in deciding on appropriate response strategies.

Spread

Under the unhindered spread scenario, the potential distribution of Varroa at the end of 5, 10 and 30 years following its entry through the port of Melbourne is shown in figure 7. Under this scenario, the results indicate that Varroa would be widespread across the eastern seaboard within 10 years, reaching saturation—the environmental carrying capacity or point of maximum pest spread and density—by 18 years.

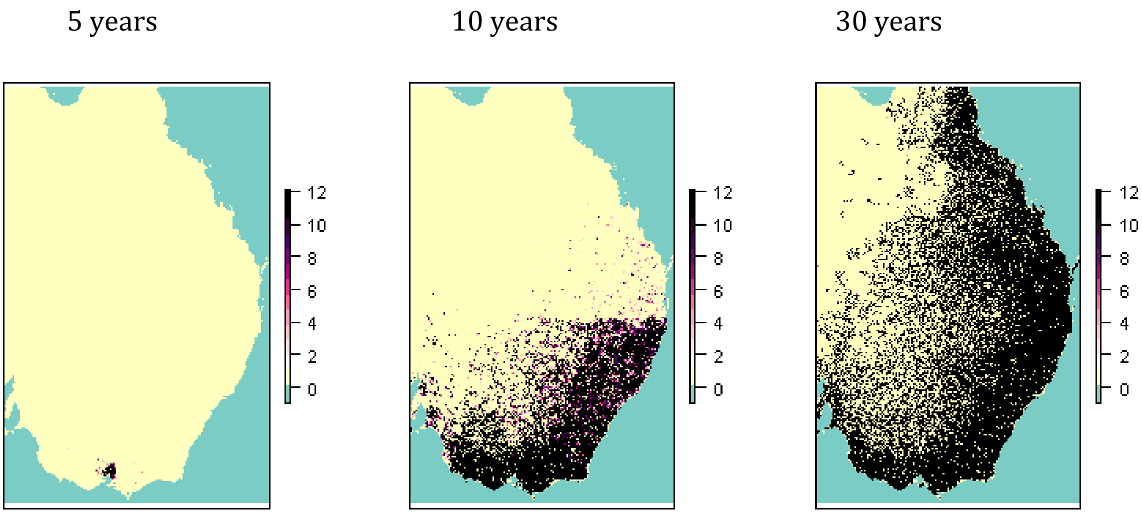
Figure 7 Unhindered spread over time originating from Melbourne



Note: The scale refers to the number of months Varroa has been present in a cell.

In comparison, figure 8 displays the potential distribution of constrained spread of Varroa at the end of 5, 10 and 30 years following an incursion in the port of Melbourne when containment strategies are in place. As can be seen, there is less spread into Queensland after 10 years under this scenario compared with the unhindered case, and Varroa does not reach its maximum spread and density until around 25 years.

Figure 8 Spread over time from Melbourne with containment



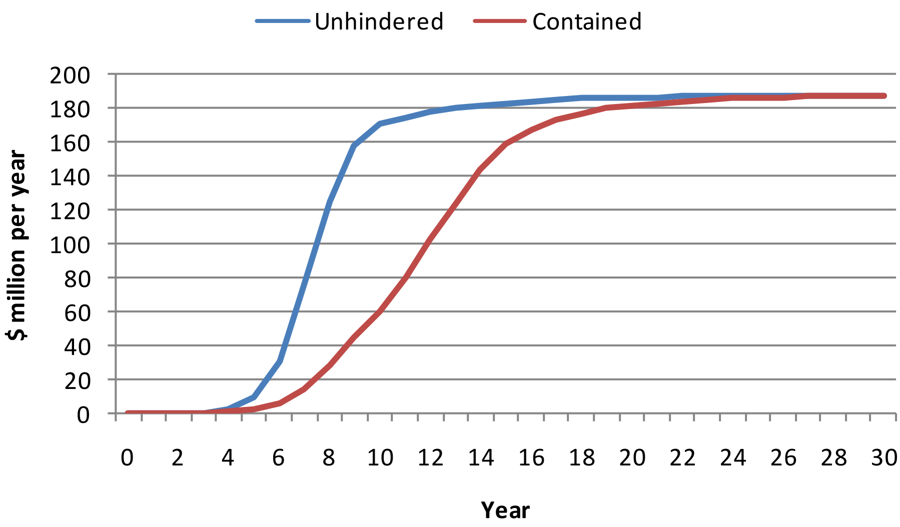
Note: The scale refers to the number of months Varroa has been present in a cell.

Economic losses

As previously discussed, estimated economic losses over time are underpinned by the establishment, expansion and saturation stages of a Varroa incursion. As Varroa spreads during the expansion stage, the rate at which areas are affected increases, and there is a rapid increase in the economic losses. As the pest spread reaches saturation, the maximum potential area is experiencing production losses, and the annual expected economic losses are at a maximum—estimated to be around $187 million per year.

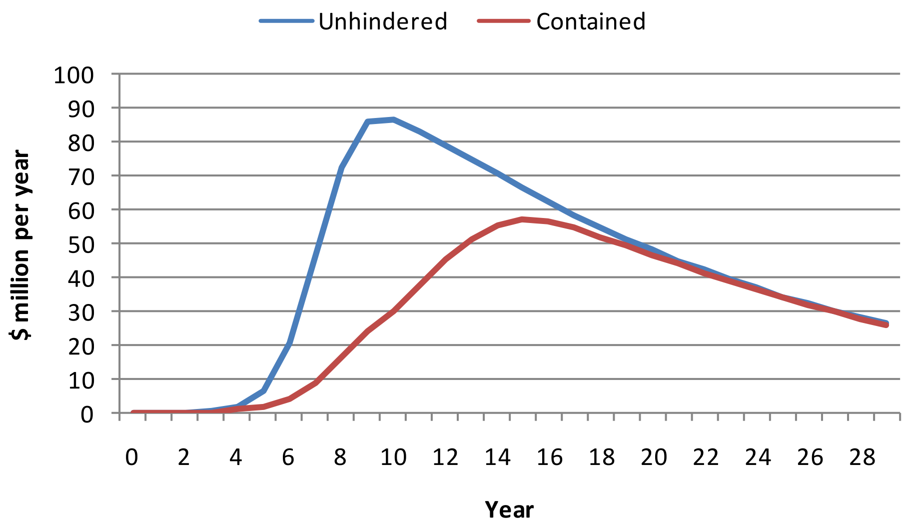
An example of these stages of spread, and associated economic losses (undiscounted), is presented in figure 9 for an incursion of Varroa originating from the port of Melbourne. Here, the yearly economic losses under both unhindered and contained spread are presented. The maximum economic losses are reached after 18 years under the unhindered spread scenario, and after 25 years under the contained spread scenario (figure 9). The economic losses are relatively smaller for contained spread until it reaches the point of maximum saturation when the yearly losses under both scenarios become the same.

Figure 9 Undiscounted economic losses overtime for a port of Melbourne incursion



The discounted yearly economic losses are presented in figure 10. This shows that the maximum economic losses are reached after 10 years under the unhindered spread scenario, compared with 15 years under the contained spread scenario. The maximum of the discounted yearly economic losses is reached at the point when the yearly increase in undiscounted economic losses equals the offsetting effect of discounting. This happens as undiscounted yearly losses begin to increase slowly, before settling at a maximum for the remainder of the 30-year period, while they are being increasingly discounted over time. The maximum discounted yearly losses are reached earlier than the maximum undiscounted losses presented in figure 9. The present value of yearly economic losses declines overtime after reaching the point of maximum.

Figure 10 Discounted economic losses over time for a port of Melbourne incursion



Note: Discounted values are calculated at a discount rate of 7 per cent.

The present values of the economic losses are calculated by summing the yearly discounted values over the 30-year period of analysis. Under the unhindered spread scenario, the estimated potential losses range from $0.63 billion to $1.31 billion, in present value terms, over 30 years, depending on the port of entry (table 2). If the spread of Varroa could be slowed through containment, the estimated economic losses, in present value terms, range from $0.36 billion to $0.93 billion, depending on the port of entry.

Under both spread scenarios, incursions from either the port of Sydney or port of Melbourne have higher losses than incursions from the port of Cairns. This is because the time taken for Varroa to spread and affect the bulk of Australia's horticultural production, which is located in the temperate regions of New South Wales and Victoria, is longer for a Cairns incursion.

Table 2 Present value of economic losses over 30 years, by port of entry and spread scenario

Port of entry and spread scenario	Economic losses		
	Producer ($m)	Consumer ($m)	Total ($m)
Sydney			
Unhindered	647	604	1 251
Contained	427	398	825
Melbourne			
Unhindered	679	634	1 313
Contained	483	450	933
Cairns			
Unhindered	324	303	627
Contained	184	171	355

Note: Present value calculated at a discount rate of 7 per cent.

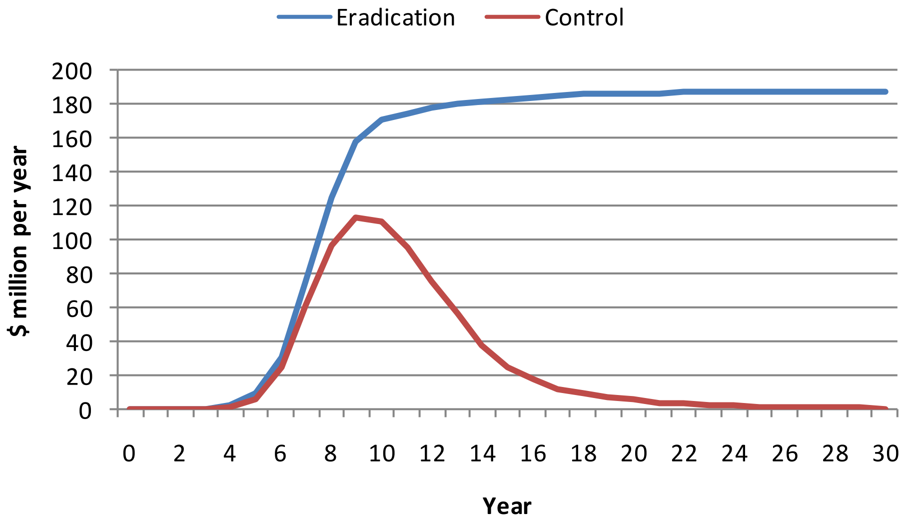
The economic losses distributed among producers and consumers have been estimated and are presented in table 2. Across the spread scenarios and ports of incursion, roughly 48 per cent of total economic losses can be attributed to the losses experienced by consumers. These consumer losses are driven by both higher prices for crop-affected products and a consequential reduction in the quantities consumed.

The maximum yearly undiscounted economic losses are estimated at around $187 million per year, which is significantly lower than the yearly loss estimates in some previous studies. For example, Gordon and Davis (2003) estimated losses to be $1.7 billion per year, but this assumed a complete loss of pollination services by honey bees. Unlike the current study, the estimates of Gordon and Davis (2003)—as acknowledged by these authors—did not factor in the offsetting effect of an expansion of managed pollination services to meet the increased hive demand. The modelling framework used in this study also produces a similar result if the pollination market module is not activated. This highlights the crucial role that an expanded managed pollination industry could potentially play in helping to reduce economic losses from an incursion of Varroa.

Benefits of response strategies

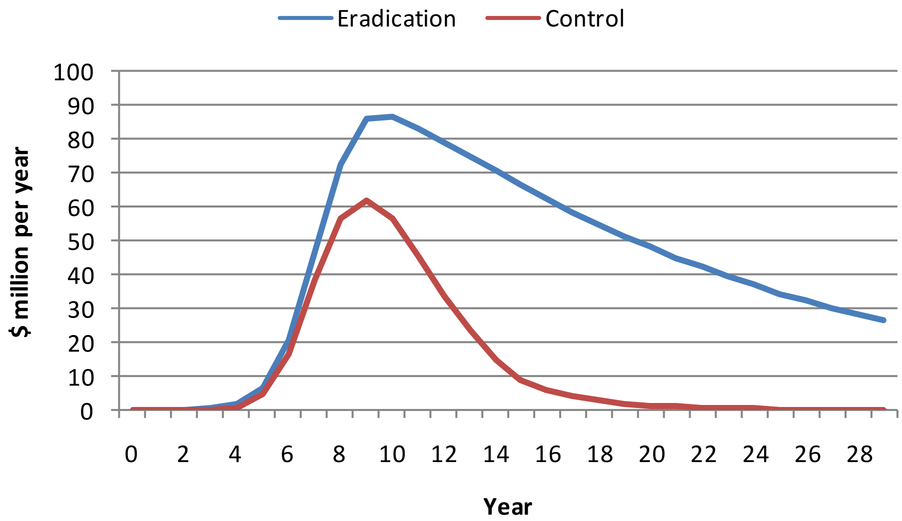
The benefits of successful eradication and containment response strategies for an incursion originating from Melbourne are presented in figure 11. The benefit curve for eradication reflects the yearly losses (now avoided) associated with the unhindered spread scenario presented in figure 9. As can be seen, the yearly benefit of eradication is at a maximum of roughly $187 million from year 18. The benefit curve for containment reflects the difference in yearly losses between the unhindered and the contained spread scenarios presented in figure 9. For the containment response strategy, a maximum yearly benefit of roughly $114 million is reached in year 10, when this difference in yearly losses (now avoided) is at maximum. However, after year 10 the yearly benefit declines and by year 25, when spread and losses are each expected to be at a maximum under both spread scenarios, losses per year are the same, as there is no longer any benefit of control. Discounted values of these yearly benefits are presented in figure 12.

Figure 11 Undiscounted benefits over time for a port of Melbourne incursion



As explained previously, for simplicity it has been assumed the benefits of eradication are equivalent to the economic losses under the unhindered spread scenario, which range from $0.63 billion to $1.31 billion over 30 years, depending on the port of entry (table 3). The benefits of slowing the spread through containment could range from $0.27 billion to $0.43 billion, in present value terms, depending on the port of entry.

Figure 12 Discounted benefits over time for a Melbourne port incursion



Note: Discounted values are calculated at a discount rate of 7 per cent.

Table 3 Present value of benefits of eradication and control over 30 years, by port of entry

Port of entry and response strategy			Benefits
	Producer ($m)	Consumer ($m)	Total ($m)
Sydney			
Eradication	647	604	1 251
Containment	220	206	426
Melbourne			
Eradication	679	634	1 313
Containment	196	184	380
Cairns			
Eradication	324	303	627
Containment	140	131	272

Note: Present value calculated at a discount rate of 7 per cent.

Movement controls were found to have the highest benefit for an incursion originating from the port of Sydney. This is because a greater number of migratory beekeepers are located in New South Wales and movement controls—preventing beekeepers from crossing state borders—will reduce a greater number of long-distance movements that could spread Varroa, helping to delay spread and the effects of an incursion.

Considerations in interpreting results

In interpreting the results presented above, a number of caveats need to be considered. These include:

- the losses presented were average estimates obtained from a large number of model simulations of Varroa spread; that is, they do not reveal the distribution of the losses around the average
- the losses to producers and consumers of pollination-dependent crops include payments to pollination and allied support services industries
- the possible switching from pollination-dependent to non-pollination-dependent crops to offset producer losses is not taken into account
- the effects of the differences in regional supply and demand for horticultural products at different times of the year are not factored into the estimated losses
- the practice of moving hives to locations in northern New South Wales and Queensland for overwintering is not taken into account.

The implications of these caveats are discussed below.

Distribution of losses due to spread rate uncertainty

The estimated impacts presented above are the average of estimates obtained from 60 model simulations of Varroa spread produced by the stochastic spread model. In each model run, Varroa spreads at a different rate, as determined by varying the spread parameters randomly. The stochastic process of Varroa spread is driven by two sources of uncertainty: first, the behaviour of the host (both feral and managed honey bee colonies); and second, the spatial spread of the parasitic pest (Varroa) from a given grid cell to the neighbouring cells. Each model run produces a different time path of spread and thus the estimated losses vary.

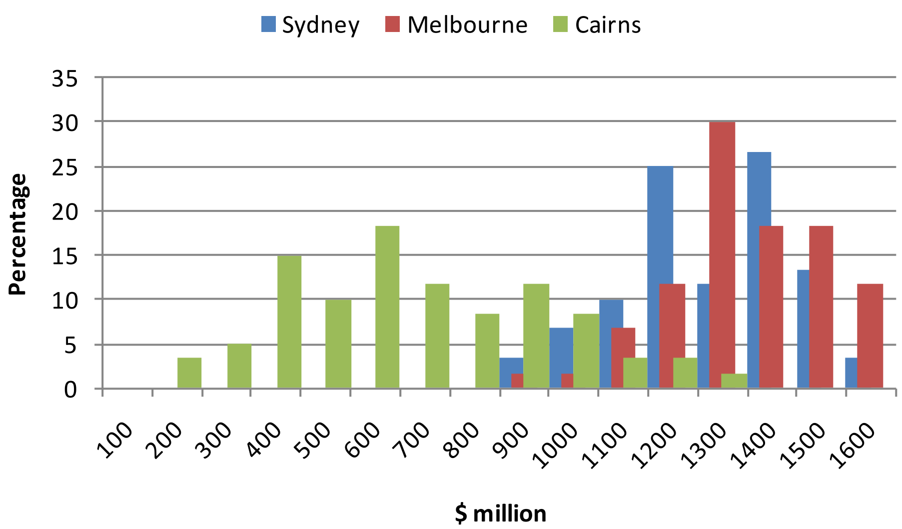
The results obtained from 60 simulations of the model run showed that the losses from unhindered spread ranged from $0.84 billion to $1.56 billion for a Melbourne incursion, with the average lossess estimated at $1.31 billion. The summary statistics for all three ports are given in table 4, while frequency distributions of losses are presented in figure 13.

Table 4 Loss summary statistics for unhindered spread under stochastic simulation

	Minimum	Maximum	Mean	Standard deviation
	$m	$m	$m	$m
Sydney	823	1 550	1 251	171
Melbourne	839	1 555	1 313	152
Cairns	130	1 224	627	251

Note: Present value calculated at a discount rate of 7 per cent.

Figure 13 Distribution of economic losses from unhindered spread



As can be seen in figure 13, the distribution of economic losses for a Cairns incursion is greater than for incursions from Sydney or Melbourne. One factor influencing this distribution is the distance of Cairns from the major horticulture regions in New South Wales and Victoria. This distance allows greater variation in the speed and paths of spread.

Payments for pollination services

The economic surplus losses estimated in the previous section relate only to the losses of producers and consumers of pollination-dependent crop products. A large proportion of these losses are payments to pollination service providers. It is estimated that these payments are equivalent to around 93 per cent of the economic surplus losses (table 5). The payments for pollination services includes both the net income gains (producer surplus) for pollination service providers and the additional input costs for expanding the pollination industry to meet higher demand. The net income gain for pollination service providers could not be estimated because the cost structure of this expanding industry is not known. The remaining economic surplus losses (around 7 per cent) are a result of lower production and consumption of pollination-dependent crops due to increases in the cost of production.

Table 5 Discounted payments for pollination services

	Economic surplus loss ($m)	Payment for pollination ($m)
Sydney	1 251	1 165
Melbourne	1 313	1 223
Cairns	627	585

Note: Discounted value is calculated at a discount rate of 7 per cent.

Effect of switching to non-pollination-dependent crops

The impact on profit margins of crop producers from additional pollination costs depends on the honey bee pollination dependence of crops and the ability to pass the increased cost on to consumers. With profits from pollination-dependent crops potentially reduced relative to alternative enterprises, it would be expected that this would provide incentives for crop producers to switch to alternative enterprises.

In the short run, however, a crop producer's decision to switch to an alternative enterprise depends on the extent of capital invested in pollination-dependent crops and how fixed this capital is; for example, whether the enterprise is based on perennial horticultural crops, and the suitability of the land for alternative crops. In the case of perennial horticultural crops, the switching decision depends on the age of the trees, how close the trees are to their replacement age and the cost for removing the trees. Hence, it is expected that initially most producers are unlikely to switch from existing crops.

In the long run, it is expected that some pollination-dependent crop producers, particularly those with low profit margins and no other options for mitigating losses, would switch production to other enterprises. Such mitigating actions by producers would reduce the estimated total economic losses from a Varroa incursion.

Estimating the mitigation of economic losses from producers switching to alternative enterprises is a difficult task as it involves solving complex resource allocation problems. Moreover, given the regional differences in land suitability for crops, it needs to be estimated at a regionally disaggregated level. The current modelling framework does not have the capacity to capture such complex resource allocation decisions and, as such, this effect has not been estimated in this study.

Effects of seasonality and regional difference in supply and demand for horticultural produce

In the initial stages, the effects of a Varroa incursion are likely to be confined to the state where the incursion occurred. While the market module takes into account the different mix of crops between states, it is not possible to capture differences in regional supply and demand balances for horticultural products at different times of the year. For example, Queensland is a major supplier of horticultural produce to eastern seaboard markets during winter months. Therefore, a Varroa incursion through the port of the Cairns could result in major disruptions to supply of some horticultural crops and lead to significant increases in prices for these products. As a result, average horticulture product prices could be higher in the initial years of incursion than those estimated in this study.

Effects of overwintering of hives

Managed hives are often moved from Victoria to northern New South Wales and Queensland for overwintering. If an incursion of Varroa through the ports of Sydney and Cairns occurred at this time, it could affect the managed hives earlier than modelled. However, if this situation did eventuate, beekeepers would be expected to move hives to locations outside any declared quarantine zones to minimise the risk of being infested, which would mitigate any additional advance effects arising from the overwintering of hives.

Sensitivity analysis of honey bee pollination dependence

The honey bee pollination dependence of crops is a key parameter in the modelling framework, as it determines the demand for, and price, of managed hives and therefore the increase in the cost of crop production because of a Varroa incursion. There is a reasonably wide range of estimates on the percentage of crop production that depends on honey bee pollination, as reported in Cook et al. (2007), Cunningham et al. (2002), Gordon and Davis (2003), Keogh et al. (2010), Monck et al. (2008) and Morse and Calderone (2000). Given the significance of this parameter, a sensitivity test is conducted on the extent to which the estimated losses reported above vary with changes in the crop pollination dependence parameters.

Table 6 sets out the extent to which the present values of the economic losses under the two scenarios vary — 10 per cent higher or lower assumed values for the percentage of production dependent on honey bee pollination for each crop. A 10 per cent decrease (increase) in the pollination dependence is estimated to result in around a 23 per cent reduction (increase) in the estimated losses. The result is consistent with a relatively inelastic supply of managed hives.

Table 6 Present value of economic losses under differing honey bee pollination dependence parameters

	Estimated losses[a]	10 per cent less dependent	10 per cent more dependent
	$m	$m	$m
Unhindered spread			
Sydney	1 251	959	1 535
Melbourne	1 313	1 007	1 610
Cairns	627	482	769
Contained spread			
Sydney	825	635	1 013
Melbourne	933	718	1 141
Cairns	355	275	435

a From the honey bee pollination dependence for crops presented in table 1.

Note: Present value calculated at a discount rate of 7 per cent.

Sensitivity of economic losses to change in discount rate

Future losses in this study were discounted with a 7 per cent discount rate to account for the time preference of money. This rate was chosen based on advice from the Office of Best Practice Regulation of the Department of Finance and Deregulations (Australian Government 2010). The effect on the estimated economic losses of a 1 per cent change in the discount rate was measured (table 7). This sensitivity analysis found that a 1 percentage point change in the discount rate (equivalent to around a 14 per cent change) could result in 14-25 per cent change in the estimated losses of various scenarios examined. The Cairns entry scenarios recorded the largest change as Varroa takes longer to saturate all habitats in Eastern Australia. Additionally, for each port of entry, the percentage change in the estimated losses is greater for the slower contained spread scenario. This sensitivity analysis suggests that the discount rate is a crucial parameter used in the study with significant implications on the returns on investment in response measures discussed in the next section.

Table 7 Present value of economic losses under differing discount rates

	6 per cent	7 per cent	8 per cent
	$m	$m	$m
Unhindered spread			
Sydney	1 461	1 251	1 076
Melbourne	1 528	1 313	1 134
Cairns	763	627	517
Contained spread			
Sydney	989	825	691
Melbourne	1110	933	788
Cairns	442	355	287

Evaluation criteria

In the event of a Varroa incursion, the benefits estimated in this study for eradication and containment provide a benchmark against which biosecurity decision-makers can compare the estimated costs of implementing these respective plans. In determining if it is economically feasible to undertake a response strategy, it is also important to consider the probability that the response will be successful in achieving the stated goal.

Ordinarily, if the costs of implementation and benefits of a response plan are known with certainty, then the economic feasibility of a response can be determined by examining the net present value (NPV)—the difference between the sum of the future stream of discounted benefits and the sum of the future stream of discounted costs.

If the NPV is positive, then the expected benefits of a strategy exceed its costs. The NPV provides an estimate of the absolute magnitude of the present value of net benefits resulting from the use of resources and can be used to rank strategies. However, as discussed below, the cost of implementing the response strategies could not have been estimated for this study. Instead, threshold probability estimates are provided for varying cost estimates, to examine the minimum probability of success required for the benefits to exceed the costs.

Costs

The cost of a response will vary with the size and location of an incursion, the specific programs included and the resources employed to undertake it. In the case of a Varroa incursion, resource variations could include labour, chemicals and equipment employed in response plan programs such as:

- tracing and surveillance

- quarantine and movement controls
- decontamination and sanitary disposal of facilities
- testing and treatment of infested bee colonies
- conducting awareness campaigns
- compensating beekeepers for destroyed hives or lost income from movement controls.

In an actual incursion, all of these programs may not be implemented. The programs implemented and the scale and intensity of each program will depend on the size and the location of the incursion. The cost of responding to an incursion cannot be estimated until the size and intensity of an incursion are known and the exact response plan has been outlined. This is highlighted by the differing estimated costs for eradicating and containing Varroa from the North Island and South Island of New Zealand (box 3). However, once the costs of the response plan have been determined for an Australian incursion, they can then be compared with the benefits estimated in this study to gauge the economic feasibility of eradicating or containing Varroa.

Box 3 New Zealand's eradication and containment strategy costs for Varroa

Following the discovery of Varroa in the North Island, the cost of eradication was estimated at NZ$55 million (New Zealand Audit Office 2002) based on the discovery of 309 infested apiaries. However, with eradication deemed to be technically infeasible, the decision was made to fund a control program with movement controls, surveillance, treatments, extension services, research and administration. The combined costs for the two-year program was NZ$7.7 million (Biosecurity New Zealand 2001), with NZ$1.5 million paid to beekeepers as compensation for colony losses (Biosecurity New Zealand 2003).

When Varroa was discovered on the South Island—it was initially identified in 41 sites within a 10 kilometre radius of Nelson—the cost of eradication was estimated to be between NZ$8 million and NZ$9 million (Somerville 2008). The New Zealand Government allocated NZ$3.2million to a management program, over four years, to slow the spread of Varroa, in addition to the NZ$2.4 million allocated to responding to the Nelson Varroa find (Biosecurity New Zealand 2006).

Uncertainty of response plan success

There is a degree of uncertainty surrounding the success of a response strategy and the likelihood of realising the estimated benefits (avoided losses). The results presented in this study have been estimated assuming 100 per cent implementation success. However, uncertainty should be incorporated into the evaluation process by comparing the costs of a response to the expected benefit—estimated benefit weighted by the probability of success. Following Hinchy and Fisher (1991), the expected benefit ($E[B]$) of a response strategy is calculated as:

$$E[B] = p_s \times B_s + (1 - p_s) \times B_f$$

Where: $E[B]$ is the expected benefit ($ million in present value terms); p_s is the probability of success in achieving the stated objective ($0 \leq p_s \leq 1$); B_s is the benefit of the response strategy if successful ($ million in present value terms); and B_f is the benefit of the response strategy if unsuccessful ($ million in present value terms).

Since the probability of success is often unknown before undertaking a response strategy, one approach for decision-makers is to use a break-even or threshold probability (p_s^*) that equates the expected benefit to cost:

$$C = p_s \times B_s + (1 - p_s) \times B_f$$

Therefore, the threshold probability is derived as follows:

$$p_s^* = \frac{C - B_f}{B_s - B_f}$$

For simplicity and illustrative purposes, it is assumed that the benefits of an unsuccessful eradication are set equal to zero. This results in an alternative threshold probability being derived as follows:

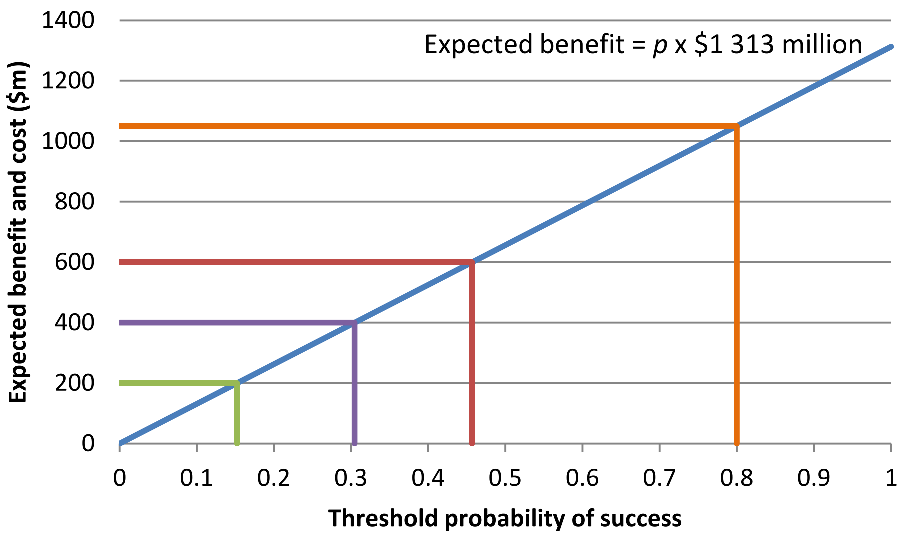
$$p_s^{**} = \frac{C}{B_s}$$

In practice, an unsuccessful response strategy may have some benefits; for example, by marginally slowing the spread of a pest. However, these benefits cannot be estimated at this stage because they depend on the effectiveness of the response measures and the stage when the response strategy efforts are abandoned. On the contrary, in the event of an actual incursion of Varroa, these benefits could be known and, as such, the threshold probability estimated (p_s^*) would be less than the value estimated assuming zero benefits of an unsuccessful eradication.

In the case of a Melbourne incursion, if the cost of eradication is assumed to be $0.20 billion, then for the estimated benefits ($1.31 billion) to outweigh the cost of eradication the probability of success must be greater than 15.3 per cent (figure 14). If the assumed cost is increased to $0.40 billion, the threshold probability increases to 30.5 per cent and at $0.60 billion it increases to 46.8 per cent. That is, the greater the cost of implementing a response strategy, the greater the probability of success required for the program to be economically feasible. Alternatively, the threshold probability can show the maximum expenditure on a response given a probability of success. For example, if an eradication campaign has an 80 per cent probability of success, to be economically feasible it should not cost more than $1.05 billion.

Demonstrated graphically, the threshold probability occurs where the cost and expected benefit lines intersect (figure 14). If the benefit is greater than the cost for a given probability, then the response is economically feasible.

Figure 14 Benefits and cost of eradication for a Melbourne incursion under uncertainty



Given the sensitivity of the estimated benefits to changes in the discount rate, it follows that the estimated threshold probabilities would also be sensitive to changes in discount rate. The sensitivity of the threshold probability to changes in the discount rate would increase where, the control expenditure occurs in the early years while benefits accrue over a longer time frame. For example, if the future discount rate is lower (higher) the threshold probabilities would also be lower (higher).

Potential application of the modelling framework

In general terms, the bio-economic model used in this study integrates three modules: (1) a spatially explicit biological spread module of a pest; (2) a partial equilibrium module of the markets for directly affected commodities; and (3) a partial equilibrium module of an integrated market for an input used by the commodity sectors to mitigate the effects of the invasive species. The general framework can be adapted to estimating the market impacts of a number of pests. A key feature of the model is its capacity to express the pest spread measured at a finer resolution (on 5 x 5 kilometre grid) in terms of proportion of the area of each SLA affected. This enables the pest spread to be directly linked to SLA-level datasets on area and production of affected commodities, and a pest's impact on affected commodities to be estimated.

The central driver of the pest spread process is the specified dispersion for the pest for each grid cell. When adapting the spread module to different pests, the parameters of the dispersion need to be respecified to suit the characteristics of the pest being studied. In addition, habitat suitability datasets also need to be redefined and the current infested areas need to be represented if the pest has already been introduced and is spreading. Changes to the commodity market module involve replacing the existing group of commodities with commodities that are affected by the pest being studied.

Appendix A—Members of the technical working group

The technical working group was formed to provide relevant expertise for the development of the benefit–cost analysis framework. Members of the technical working group were:

- George Antony—Department of Employment, Economic Development and Innovation, Queensland
- David Cook—Commonwealth Scientific and Industrial Research Organisation
- Scott Davenport—Department of Primary Industries, New South Wales (NSW DPI)
- Iain East—Office of the Chief Veterinary Officer, Australian Government Department of Agriculture, Fisheries and Forestry (DAFF)
- Russell Goodman—Department of Primary Industries, Victoria
- Gerald Martin—Pollination Australia R&D Committee
- Glynn Maynard—Office of the Chief Plant Protection Officer, DAFF
- Terry Ryan—Australian Honey Bee Industry Council
- Harley Smith—NSW DPI
- Stewart Webster—NSW DPI
- National Biosecurity Committee Secretariat—DAFF

Appendix B—Technical details of the Varroa spread modelling

The spread of Varroa within managed and feral *Apis mellifera* colonies was modelled on a 5 x 5 kilometre raster layer. Modelling was undertaken within the R computing environment (2008). The 5 x 5 kilometre resolution was considered appropriate to the system being modelled. The scale largely encompasses the typical movements of an *Apis mellifera* colony, but is small enough to have interactions between neighbouring cells over a monthly time frame.

Habitat suitability

A crude habitat suitability layer of each cell to host feral *Apis mellifera* colonies was generated from a simple classification model that returned the probability of a raster cell being suitable for feral honey bees' survival based on annual rainfall and maximum summer temperatures. Parameter values for the classification model were tuned so that the resulting distribution of feral *A. mellifera* colonies broadly matched that described by Technical Working Group members. During each model run, raster cells were classified as suitable (or not) for feral honey bees, based stochastically on the cell probabilities.

Varroa spread

The model accounts for Varroa spread through feral honey bee populations, from feral honey bees to commercial hives, within commercial enterprises, and from commercial enterprises back to feral honey bees. The model does not explicitly include transmission between commercial enterprises from activities such as trade in hives, or from queen breeders to commercial enterprises. However, transmission between commercial hives will occur if the enterprises share sites, and is possible if the hives are located nearby (see below). Transmission via infected queen breeding operations could result in rapid dissemination of mite infestation across the country.

Apiary sites

Approximately 90 per cent of hives in Australia are operated by just 1700 beekeepers, who operate more than 50 hives each (Crooks 2008). It was assumed that these 1700 'large' beekeeping enterprises were located in Eastern Australia (including South Australia) and in each year they worked their hives over an average of approximately 7 sites. The actual number of sites per enterprise was modelled as arising from a Poisson distribution, meaning that 95 per cent of beekeepers worked between two and 13 sites over a year.

The survey of beekeepers with 100 hives or more by Bresolin and Peterson (2010) was used to generate a spatial layer of the density of hives by Statistical Local Area (SLA), by month. The response rate for this survey was about 20 per cent and it was apparent that there were many gaps in the distribution where managed hives were undoubtedly located but not identified by the survey. To alleviate this, data were pooled across months to get an average frequency of hive use across the year, by SLA. Where gaps in the data still persisted, the minimum frequency observed was imputed. This frequency data were then converted to spatial intensity by correcting for the area of each SLA.

For each model run, the 'home' apiary site for each enterprise was generated by sampling from all grid cells, with the probability of selection weighted according to the hive frequency for that cell. Subsequent sites within each enterprise were randomly generated in a similar manner, but weighted by both habitat suitability and beekeeping frequency and restricted to be within 650 kilometres of the home apiary site.

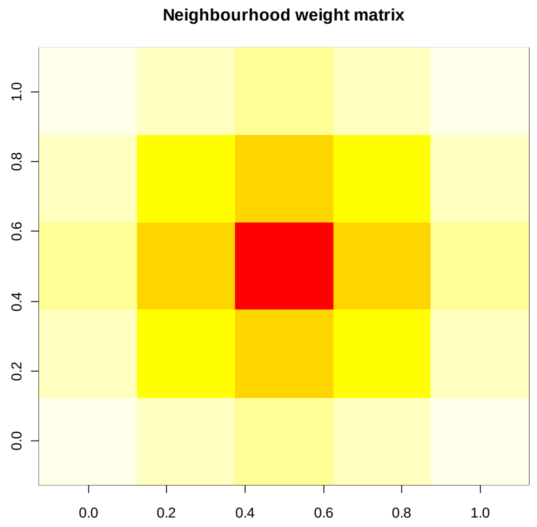
Spread within beekeeping enterprises

The monthly reproduction number per apiary site was set to 0.1. This is the monthly rate at which new infected sites are generated per infected site. In essence, this equals the probability that the site contains hives, multiplied by the monthly rate of movement to a new site given that hives are present. For example, if 20 per cent of sites are occupied then a monthly movement probability of 0.5 (that is, hives stay for an average of two months at each site) would be consistent with the parameterisation. At each time step, the number of infected sites within an enterprise was calculated, and the probability of other sites within the enterprise becoming infected was calculated based on the aggregate infection pressure within the enterprise. Whether or not infestation occurred was determined stochastically at each time step.

Spread between beekeeping enterprises

Spread between neighbouring cells was modelled as a stochastic jump-diffusion process. The probability that an uninfected cell will transition to being infected in each time-step is determined by the neighbourhood weight matrix, shown diagrammatically in figure B1. This indicates that over a time-step of one month, transmission of mites occurs to a maximum of two cells away (approximately 10 kilometres), with most transmission, if any, occurring in cells immediately neighbouring infected ones.

Figure B1 Degree of influence a cell has on neighbouring cells



For any uninfected cell, the probability of transmission/infestation is derived by considering the neighbourhood weighting arising from all infected cells. Whether or not transmission occurs is determined by jointly considering the effect of all infected cells. This was achieved using the neighbours() function in the library simecol (Petzoldt & Rinke 2007). Parameters governing the spread process were tuned to give an average spread rate of approximately 1 kilometre per month over the first 18 months of the incursion, based on the findings of Stevenson et al. (2005).

Reductions in bee numbers

For each raster cell, a record was kept of the duration of infestation. Feral bee numbers were assumed to decrease linearly following infestation, with maximum reduction occurring after 12 months of infestation. This could easily be changed to account for logistic-type growth, although the resulting differences will be small. At each time-step, the overall reduction in feral bee populations within each SLA was calculated as the time-weighted proportion of cells infected. It was assumed that once a cell became infected it remained infected, and there was no discernible recovery in feral bee numbers (in contrast with Harris et al. 2003).

Interventions

Two types of interventions are able to be implemented in the model runs. First, a buffer zone around ports can be created that does not allow any hive movements within this zone. The radius of the buffer in preliminary runs has been set at 50 kilometres. Second, movement restrictions may be implemented preventing hives being moved across state boundaries. In this situation, within-enterprise movements continue on either side of the border for those enterprises whose apiary sites are located in more than one state. Apiary sites in this situation may adjoin the border, and interstate transmission occurs via cell-to-cell 'creep' as opposed to 'accelerated' spread arising from hive movements.

Appendix C—Algebraic representation of market models

The market model has three modules: (1) a commodity market module; (2) a pollination market module; and (3) a pest spread module linking the results obtained from the spatially explicit spread model to the integrated commodity and pollination market model. The key features of the modelling framework are listed in the first column of table B1. The extent to which these features exist in three other comparable models are shown in the remaining columns of table C1.

Table C1 Modelling framework key features relative to previous studies

Current model feature	Monck et al (2008)	Cook et al. (2007)	Gordon and Davis (2003)
Pest spread over time	No	Yes	No
Pest spread over space	No	No	No
Impact on consumers	Yes, but not reported	No	Yes
Impact on producers	Yes	Yes	Yes
Producers respond to price increase	Yes	No	Yes
Adjustment in exports and imports	Yes	No	Yes
Use economic surplus measures	No	No	Yes
Mitigation and adaptation	Yes, particularly the supply adjustment by pollination industry	Yes (partial)	Yes (partial)
Representation of the bee market	Yes	No	No
Response of beekeeping industry to increased demand for hives	Yes	No	No
Simulate the avoided losses with alternative management scenarios	No	No	No
Factor in uncertainty	No	Yes	Yes
Frequency distribution of avoided losses	No	Yes	No

An algebraic representation of each module is presented below. The equilibrium values for variables included in the integrated commodity market and pollination market modules are determined endogenously in the process of solving the simultaneous equations (1)–(11). The model is formulated as a Mixed Complementarity Programming problem using the General Algebraic Modelling System (GAMS) and solved using the PATH solver.

Commodity market module

A separate commodity market module is specified for each of the 35 crops included and is run for each year of the 30-year planning horizon. However, to avoid notational clutter, the commodity and time indexes are omitted intentionally in the algebraic representation presented below.

Variables

qs = quantity supplied (tonnes/year)

qd = aggregate quantity demanded of both imported and domestically produced product (tonnes/year)

$qdom$ = quantity of domestically produced product demanded (tonnes/year)

qimp	=	quantity imported (tonnes/year)
qexp	=	quantity exported (tonnes/year)
pdom	=	price of domestically produced product ($/tonne)
pimp	=	price of imported product ($/tonne)
pd	=	value share weighted price of product ($/tonne)
pcst	=	increase in marginal cost due to the use of hired pollination ($/tonne)

Parameters

α	=	*scale term of the supply function*
β	=	*scale term of the domestic aggregate demand function*
θ	=	*scale term of the export demand function*
μdom	=	*scale term of the domestically sourced to total consumption share function*
μimp	=	*scale term of the imports to total consumption share function*
εs	=	*elasticity of supply*
εd	=	*elasticity of aggregate domestic demand*
εx	=	*elasticity of export demand*
σ	=	*elasticity of substitution in consumption between domestically produced and imported products*
γ	=	*proportionate reduction in pollination-dependent production*

$$qs = \alpha(pdom - pcst)^{\varepsilon s} \times (1-\gamma) \qquad (1)$$

$$qd = \beta pd^{\varepsilon d} \qquad (2)$$

$$pd = \frac{pdom \cdot qdom + pimp \cdot qimp}{qd} \qquad (3)$$

$$\frac{qdom}{qd} = \mu dom \left(\frac{pdom}{pd}\right)^{-\sigma} \qquad (4)$$

$$\frac{qimp}{qd} = \mu imp \left(\frac{pimp}{pd}\right)^{-\sigma} \qquad (5)$$

$$qexp = \theta pdom^{\varepsilon x} \qquad (6)$$

$$qs = qdom + qexp \qquad (7)$$

A key distinguishing feature of the market module is that it treats domestically produced and imported varieties of the same product as imperfect substitutes. In the model, domestic producers and exporters respond to domestic price, while domestic consumers respond to weighted average price of domestic price and import price.

Quantity supplied is a constant elasticity function of domestic price (equation 1), while aggregate demand is a constant elasticity function of the weighted average price of domestic and import prices (equation 2).

Weighted average price of domestic and import prices is calculated by using quantity of domestically produced product consumed and imports as weights (equation 3).

The share of domestically produced products in aggregate consumption is a constant elasticity function of the ratio of domestic price to weighted average price (equation 4)

The share of imports in aggregate consumption is a constant elasticity function of the ratio of import price to weighted average price (equation 5).

Quantity of exports is a constant elasticity function of domestic price (equation 6).

Quantity of domestic product demanded by domestic and foreign consumers (exports) cannot exceed the supply of domestic production (equation 7).

Pollination services market module

Index

c	=	*crop c=1..,...35*

Variables

$qdhv_c$	=	aggregate number of hives demanded for crop *c*
$qshv$	=	aggregate number of hives supplied by the beekeeping industry
phv	=	market price of hives ($/hive)
qs_c	=	aggregate quantity supplied of crop *c* (tonne/year)
$pcst_c$	=	cost of additional hives per tonne of crop *c* produced

Parameters

r_c	=	proportion of production of crop *c* dependent on pollination
A_c	=	number of replacement hives required per tonne of crop *c* produced (hives/tonne)
η	=	elasticity of supply of hives
π	=	aggregate number of hired hives used prior to the incursion of Varroa
λ	=	aggregate number of hired hives used prior to the incursion of Varroa

$$qdhv_C = A_c \times qs_c \times r_c \quad (8)$$

$$\sum_C qdhv_C + \pi = qshv \quad (9)$$

$$qshv = \lambda \times phv^{\eta} \quad (10)$$

$$pcst_C = A_C \times phv \quad (11)$$

For each crop, the number of hired bee hives required to replace the lost feral bee hives (LHS of equation 8) is estimated as the product of the number of feral bee hives inputs used per tonne of product c (A_c), aggregate quantity produced and proportion of production dependent on bee pollination (RHS of equation 8). The parameter A_c is estimated using the information provided in Monck et al. (2008) on potential pollination cost as a share of GVP and price of hired hives and the price of product (unit GVP) used in the commodity market module. This is done in 4 steps:

1) The cost of pollination per tonne is estimated and then the total number of both feral and hired hives per tonne is estimated by dividing this cost of pollination per tonne by the price per hive.
2) For each crop, the aggregate number of both hired and feral hives is then estimated using data on aggregate production and proportion of production dependent on bee pollination. After summing over all crops, the aggregate number of hives is estimated at 458 000.
3) Assuming a total of 200 000 hired hives are used prior to Varroa incursion, the total number of feral hives used is estimated at 258 000. Hence, feral bee hives contribute to approximately 56 per cent of the estimated total number of hives.
4) The parameter A_c, the number of feral bee hives inputs used per tonne of product, is then assumed to be equal to 56 per cent of the total number of both feral and hired hives per tonne as estimated in step 1.

The total number of hives demanded with Varroa incursion equals the total number of replacement hives required plus the total number of hired hives used prior to Varroa incursion (π) (LHS of equation 9). The parameter π is set a value of 200 000. Equation 9 shows that the total demand for hired hives cannot exceed the total supply of hives (RHS of equation 9).

Total supply of hives (LHS of equation 10) is a constant elasticity function of the price of hives (RHS of equation 11).

The cost of replacement hives per tonne (LHS of equation 11) equals the product of A_c and the price of hives (RHS of equation 11). The price of hives is solved in the process of solving all the simultaneous equations included in both the commodity market and pollination market modules that are integrated. The cost of replacement hive per tonne $pcst_c$ enters the equation (1) of the commodity market module as the pivotal shifter of the supply curve.

Linkage to spread model

Indexes

t	=	year t =1..,..., 30
sla	=	statistical local area

Variables

qp(c,t,sla)	=	reduction in production of crop *c* at the end of time *t* in *sla*

QP(c,t)	=	the reduction in aggregate production of crop c at the end of time t
QUP(c,t)	=	aggregate production of crop c still intact at the end of time t

Parameters

qp0(c,sla)	=	production of crop c in *sla* (from ABS SLA level data series)
a(t,sla)	=	proportion of *sla* area Varroa has spread at the end of time t
r(c)	=	proportion of production of crop c dependent on bee pollination

$$qp(c,t,sla) = a(t,sla) \times qp0(c,sla) \times r(c) \qquad (12)$$

$$QP(c,t) = \sum_{sla} qp(c,t,sla) \qquad (13)$$

$$QUP(c,t) = \sum_{sla} qp0(c,sla) \times r(c) - QP(c,t) \qquad (14)$$

$$\gamma(c,t) = \frac{\boldsymbol{QP(c,t)}}{\sum_{sla} \boldsymbol{qp0(c,sla)}} \qquad (15)$$

Where: $0 \leq a(t,sla) \leq 1$ and $0.1 \leq r(c) \leq 1$

At the end of each year, the spread model identifies the new Statistical Local Areas (SLAs) the pest has entered. For each year and SLA the pest has already entered by the end of that year, the spread model also estimates the cumulative proportion of the SLA area the pest has spread to, denoted by *a(t,sla).*

For each crop, year and SLA, the potential reduction in production of pollination-dependent crop, *qp(c,t,sla)* (LHS of equation 12) is given by the product of the cumulative proportion of the SLA area the pest has spread to *(a(t,sla)),* production prior to the spread of Varroa *(qp0(c,sla))* and the proportion of production dependent on bee pollination (RHS of equation 12).

For each crop and year, the reduction in aggregate production (LHS of equation 13) is then estimated by summing over all SLAs the potential reduction in production. For each crop and year, the proportionate reduction in aggregate production, γ introduced in equation 1 of the commodity market module is then calculated by dividing *QP(c,t)* by the aggregate production (production summed overall SLAs) (equation 15).

Appendix D—Industry statistics: production, trade and elasticities

	Exports a		Imports b		Domestic production		Domestic consumption		Elasticity g			
Crop	Quantity (t)	Price ($/t)	Quantity (t)	Price ($/t)	Quantity c (t)	Farmgate price d ($/t)	Quantity e (t)	Price f ($/t)	Domestic demand	domestic supply	import substitution	export demand
Almond	7 803	7 850	2 014	10 075	12 420	8 412	4 617	7 850	−2	1.25	10	−8
Apple	8 734	1 372	788	3 828	276 427	1 302	267 692	1 372	−2	0.5	10	−8
Apricot	314	5 401	605	3 630	16 920	1 409	16 606	5 401	−2	0.5	10	−8
Asparagus	4 789	4 613	1 470	3 771	9 737	4 787	4 947	4 613	−2	0.75	10	−8
Avocado	917	2 868	12 505	3 447	34 452	2 367	33 535	2 868	−2.5	0.75	10	−8
Blueberry	–	–	–	–	2 316	28 926	2 316	28 926	−2.5	0.75	3	−8
Canola	884 267	374	–	–	1 413 941	334	529 674	374	−2	1	10	−8
Canola seed	–	–	–	–	5 000	1 335	5 000	1 335	−2	1	10	−8
Cherries	978	8 202	1 069	11 629	9 783	10 010	8 805	8 202	−2.5	0.5	3	−8
Clover seed	–	–	–	–	3 000	5 000	3 000	5 000	−2	1	3	−8
Cotton lint	65 ,300	1 749	40	1 872	559 728	1 667	−90 572	1 749	−2	1	3	−8
Cucumber	265	2 441	2 345	587	23 270	2 575	23 005	2 441	−2	0.75	10	−8
Fieldpea	1 684	588	–	–	584 619	222	582 935	588	−2	1	10	−8
Grapefruit	158	1 216	624	1 156	14 893	877	14 734	1 216	−2	1.25	3	−8
Kiwifruit	1 249	2 036	18 427	1 932	5 625	2 001	4 376	2 036	−2.5	1	10	−8
Lemon & Lime	68	2 054	3 285	1 656	33 495	982	33 428	2 054	−2	1.25	10	−8
Lettuce	415	4 088		836 500	162 832	977	162 417	4 088	−2	0.75	3	−8
Lucern seed	–	–	–	–	5 000	6 600	5 000	6 600	−2	1	2	−8
Lupin	469 463	212	–	–	1 285 033	195	815 570	212	−2	1.25	3	−8
Macadamia nut	–	–	842	8 043	31 613	3 317	31 613	3 317	−2.5	1.25	3	−8
Mandarin	3 149	1 494	974	3 018	92 348	1 280	89 199	1 494	−2	1.25	3	−8
Mango	2 844	4 089	808	3 845	36 348	2 685	33 504	4 089	−2.5	1	10	−8
Nectarine	6 444	2 493	1	8 343	48 940	2 161	42 496	2 493	−2	1	10	−8
Onion	46 279	476	10 186	1 350	221 923	655	175 644	476	−2	0.75	3	−8
Orange	27 580	1 013	12 418	1 383	507 233	542	479 653	1 013	−2	1.25	3	−8
Papaya	2	3 488	174	2 370	6 456	1 471	6 454	3 488	−2	1	3	−8
Peach	1 192	3 456	1	8 343	90 630	1 190	89 438	3 456	−2	0.5	10	−8
Peanut	1 784	1 567	4 946	1 055	24 508	700	22 724	1 567	−2	1.25	10	−8
Pear	7 937	1 184	4 211	948	142 419	658	134 482	1 184	−2	0.5	3	−8

	Exports a		Imports b		Domestic production		Domestic consumption		Elasticity g			
Crop	**Quantity (t)**	**Price ($/t)**	**Quantity (t)**	**Price ($/t)**	**Quantity c (t)**	**Farmgate price d ($/t)**	**Quantity e (t)**	**Price f ($/t)**	**Domestic demand**	**domestic supply**	**import substitution**	**export demand**
Plum & Prune	5 661	2 509	0	3 306	26 355	2 034	20 694	2 509	–2	0.75	10	–8
Pumpkin	–	–	–	–	110 906	729	110 906	729	–2	0.75	3	–8
Raspberries	–	–	–	–	532	23 387	532	23 387	–2	1	3	–8
Melon (excl. watermelon)	10 662	1 305	–	–	85 020	1 091	74 358	1 305	–2	0.75	3	–8
Soybean	–	–	–	–	50 149	356	50 149	356	–2	0.75	10	–8
Strawberry	4 142	3 976	6 286	1 215	27 336	6 217	23 194	3 976	–2	0.75	3	–8
Sunflower	3 458	2 585	26 644	894	81 996	384	78 538	2 585	–2	0.75	10	–8
Watermelon	2 262	740	–	–	133 777	534	131 515	740	–2	0.75	3	–8
Zucchini	–	–	–	–	22 760	3 151	22 760	3 151	–2	0.75	3	–8
Vegetable seed	–	–	–	–	1 591	17 599	1 591	17 599	–2	0.75	10	–8

Notes: '–' indicates a zero value or data not available. For modelling purposes, assumed to be zero.

Sources: **a** ABS (2010). **b** ABS (2010). **c** ABS (2008a, 2008b); canola seed production sourced from ABARES (2010); clover seed and lucern seed (A Glenn [DAFF, Levies Revenue Service] pers.comms, January 2011). **d** ABS (2008a, 2008b). **e** Equals domestic production less exports. **f** Assumes export parity—prices as for the export market. Where there are no exports, the price per tonne was based on domestic production figures. **g** Elasticities—adapted from Gordon and Davis (2003)

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