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The future of pollinators for Australian agriculture

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Abstract. Agriculture in Australia is highly dependent on insect pollination, in particular from the introduced western honeybee, *Apis mellifera*. Most agricultural pollination is provided as an unpaid service by feral *A. mellifera* and native insects. A smaller proportion of agricultural pollination is provided as a paid service by beekeepers. Insect pollination is threatened by misuse of insecticides and the loss of remnant vegetation, but most potently by the likelihood that the honeybee mite, *Varroa destructor*, will enter the country. Now is the time to prepare for the effect of these changes, and international experience with pollinator decline should serve as a guide. We need to protect and manage our remnant vegetation to protect wild pollinators. Insurance against declining *A. mellifera* will come through the development of management practices for alternative pollinator species. By developing native insects as pollinators we can avoid the risks associated with the importation of additional introduced species.

Introduction

The honeybee, *A. mellifera*, is an introduced species now widespread in Australia in both feral and managed populations. Some of our agricultural industries are highly dependent on this species, which has become prominent in many natural ecosystems, frequently present as an efficient and abundant exploiter of floral resources and a likely pollinator of many native plants. It is the role of *A. mellifera* in natural ecosystems that has attracted most attention in the ecological literature. In this paper, we examine the future of *A. mellifera* in Australia, leaving aside debate on the magnitude of its effect on native flora and fauna and focussing instead on the consequences of a possible decline in honeybees for sustainable agriculture.

Pollinator decline has become an issue of major concern around the world (Watanabe 1994; Williams 1995; Buchmann and Nabhan 1996; Matheson *et al.*1996; Myers 1996; Allen-Wardell *et al.* 1998; Cane and Tepedino 2001) largely because of declining *A. mellifera* populations after the arrival of the parasitic mite, *Varroa destructor*. These events served to highlight the danger of neglecting the service provided by pollinators. What then are the risks in Australia? In this paper we assess the importance of insect pollination to agricultural industries, and suggest options to address pollinator decline. We refer to the international experience as a guide to the changes that Australia may be facing, and use Australian examples where possible to illustrate local problems and solutions.

Pollinators in agriculture

Some crop species do not require animal pollination as they are either wind-pollinated, self-pollinated, or reproduce vegetatively. However, many species do require the pollinator services of bees and other insects. Honeybees (*A. mellifera*) are native to Eurasia and Africa. Because of their value as a source of honey and, secondarily, as a pollinator, people have moved honeybees around the world (Westerkamp and Gottsberger 2000). *A. mellifera* was introduced to Australia repeatedly throughout the 1800s (Paton 1996). Feral honeybee populations established from managed colonies, and are now found throughout the continent except in the most arid habitats (Paton 1996). Beekeepers, concentrated in the more temperate parts of Australia, move their managed hives into areas with favourable floral resources, thus bringing those populations into a wide range of habitats at different times. Concern about the effect of both feral and managed bees has prompted research into issues including competition between *A. mellifera* and other native flower visitors, the effect of *A. mellifera* on the pollination of native plants, and competition between *A. mellifera* and native animals for nesting sites. These studies have been reviewed elsewhere (Paton 1993, 1996, 1997; Sugden *et al.* 1996; Butz Huryn 1997).

Australia’s agriculture is derived mostly from European practice and is based almost entirely on introduced species (*Macadamia* provides an interesting exception). It is not surprising, therefore, that the honeybee has been the pollinator of choice for most of our insect-pollinated crops (Free 1993). This species can pollinate a wide range of plants and its management is well understood. As the consummate floral generalist, it is not always the most efficient pollinator of any given species, but its adaptability and manageability have made it very useful in agriculture.

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There have been attempts to estimate the dollar value of crop pollination by bees in Australia, such as Gill's 1989 estimate of 0.6–1.2 billion dollars (Gill 1989*a*; Gibbs and Muirhead 1998). In this study, we are less concerned with assigning an overall dollar value than with identifying the size of the effect that a pollination decline could have on farming practice, and thereby the nature of the Australian landscape. We have therefore examined the dependence of crops on pollinators and the size of the sector affected. To illustrate the significance of pollinators in Australian agriculture, consider the Goulburn–Broken catchment of northern Victoria. In 1996, the gross value at farm gate of agricultural production in this region was greater than AU$1 billion. Almost 20% of this value was contributed by fruit and vegetables, and 40% was from dairy (Binning *et al.* 2001). As in any horticultural region, the crops grown here show a wide range of dependence on animal pollination ranging from those that set no fruit in the absence of pollinators, such as almonds or blueberries, to those that set ample fruit in the absence of pollinators, such as olives and soybeans (Table 1).

The contribution of pollinators, however, is not always best measured by their effect on fruit number. For many of the multi-seeded fruits, such as pears and apples, growers are more concerned about pollination in maximising fruit quality, rather than quantity. A well-pollinated flower will contain more seeds, which prompt the development of a bigger and better shaped fruit with superior market value (Torchio 1985; Free 1993). For some single-seeded fruits such as cherries and plums, pollination is more important for the quantity of yield. Ample pollination can also reduce the time between flowering and fruit set. By shortening this period, the risk from exposing developing fruits to pests, disease, and bad weather is reduced and there can be savings in water, fertiliser, and pesticide.

Most nitrogen-fixing pasture legumes (such as clover and lucerne) also benefit from insect pollination (Free 1993; Richards 1996). Insect pollination is therefore crucial to maintaining good grazing land, in particular high-intensity grazing such as that used by the dairy industry. Farmers generally buy seed to maintain good nitrogenous fodder in their pastures, with legumes being a key ingredient. When buying seed the farmers are indirectly paying for pollination services. This is true for seeds of vegetables such as onions and carrots, as well as clovers and lucerne for pasture. The pollination cost can be as much as 25% of the seed price (Westerkamp and Gottsberger 2000; Kevan and Phillips 2001). If legumes in the farmer's own fields are well pollinated and set ample seed, less seed needs to subsequently be purchased. Lucerne is a particularly useful nitrogen-fixing crop because, in addition to its role as a fodder plant, it is deep-rooted, salt-tolerant, and drought-resistant and can therefore play a significant role in lowering the watertable on agricultural land (Angus *et al.* 2001). The production of lucerne in Australia is currently limited by pollination problems that prevent high levels of seed production.

Insect pollination of crops in Australia comes from 3 different sources. Firstly, feral *A. mellifera* are widespread and visit many crop species. Secondly, commercial beekeepers are sometimes paid to place hives of *A. mellifera* in pollinator-dependent crops. Thirdly, native bees and other insects visit some crops. In temperate-zone agriculture and horticulture it is widely assumed that nearly all animal pollination is by *A. mellifera*. Contributions from other fauna are mostly little known. Some authors have argued that the role of *Apis* (relative to other pollinators) is generally overstated, because of ignorance about non-*Apis* pollinators (Westerkamp and Gottsberger 2000). Pollination by insects other than *A. mellifera* is better appreciated in Australian tropical horticulture, where they are understood to contribute to pollination of mango (Anderson *et al.* 1982), cashew (Heard *et al.* 1990), *Macadamia* (Heard and Exley 1994), custard apple (George *et al.* 1989), and papaya (Morrisen *et al.* 2000).

Growers of highly pollinator-dependent crops often pay beekeepers to provide bees, because feral bees cannot provide sufficient service. This is especially true for crops which, in addition to being pollinator-dependent, are relatively unattractive to *A. mellifera* and therefore must be saturated with bees to assure pollination. Kiwi fruit is one such crop (Craig and Stewart 1988). In contrast, some crops, like apples, are very attractive to bees, such that, although they benefit considerably from pollination, many growers are content with the level of pollination provided by feral bees or managed bees from a neighbouring farm. Crops with low reliance on pollinators are not usually provided with managed bees. These crops may, nevertheless, have value added by feral bees or native insects. Most broad-acre crops, such as wheat and barley, are wind pollinated or produce seed asexually, but some, like canola, are insect-pollinated. Although canola has a low reliance on insects for pollination (Table 1), wild insects cannot service the whole crop in broad-scale plantings. Therefore canola is frequently provided with managed bees; however, even when provided with beehives, decline in canola yield with increasing distance from the hive is measurable, and can amount to substantial losses (Manning and Boland 2000).

Threats to pollinators in agriculture

Varroa *mites and other diseases of* Apis mellifera

The most potent threat to pollination services comes from the aptly named *Varroa destructor*, which is a parasitic mite of *Apis* bees, including *A. mellifera*. Originating in Asia, it has now spread almost worldwide, and is regarded as the most serious pest of *A. mellifera* (Oldroyd 1999; Anderson and Trueman 2000). Early in 2000 it was confirmed that

Table 1. Crops grown in the Goulburn–Broken catchment (Vic., Australia) and the degree to which they rely on pollinators to produce fruits or seeds of good quality

A crop with 100% reliance would produce no marketable fruits or seed in the absence of pollinators. A crop with 50% reliance would produce fruits or seeds, but the crop would have half the value because of declines in the size, shape, or number of fruits. These estimates are approximate and are obtained from a range of literature, but where possible were examined in light of biological information in general crop pollination texts (McGregor 1976; Free 1993; Delaplane and Mayer 2000), and one review that examined dependency of crops on managed honeybees (Southwick and Southwick 1992). In some cases the original data were from exclusion experiments; in other cases the estimates were derived from growers' experiences. Exact values depend on crop variety and other management practices. Crops are presented in order of their reliance on pollinators. We present tonnage produced in the Goulburn statistical area for the most recent available year, from Australian Bureau of Statistics (ABS) publications. To highlight some of the more productive crops in the area, we have put in **bold** those with yield greater than 4000 t/year. Of course, some of the low tonnage crops nevertheless have considerable market value

Crop	Pollinator reliance (%)	t/year
Almond	100[A]	1.4[I]
Blueberry	100[A]	29[I]
Sunflower:		
Self incompatible var.	100[A]	300[J]
Self fertile var.	30[B]	
Lucerne	100[A]	**46 900**[J]
Pumpkin	90[A]	291[K]
Cherry	90[A]	518[I]
Kiwi	90[A]	1428[I]
Apple	90[A]	**56 470**[I]
Clover species	90[C]	Used *in situ*
Grapefruit	80[A]	316[I]
Plum	70[A]	3032[I]
Apricot	70[A]	**7984**[I]
Nectarine	60[A]	2055[I]
Peach	60[A]	**39 228**[I]
Faba bean	50[D]	1100[J]
Field pea	50[D]	2900[J]
Nashi pear	50[A]	**4348**[I]
Pear (not Nashi)	50[A]	**141 011**[I]
Strawberry	40[A]	235[I]
Mandarin	30[A]	41[I]
Orange	30[A]	**5373**[I]
Raspberry	30[E]	17[I]
Lemon and lime	20[A]	1383[I]
Canola	15[F]	**10 900**[J]
Lupin	10[A]	**10 700**[J]
Grapes	1[G]	**6325**[I]
Tomatoes (fresh + processing)	1[H]	**63 192**[K]
Olives	0[D]	10[I]
Soybean	0[D]	3700[J]

[A] Pollinator reliance from Gill (1989*a*).
[B] Pollinator reliance from Delaplane and Mayer (2000).
[C] Pollinator reliance from Goodman and Williams (1994).
[D] Pollinator reliance from McGregor (1976).
[E] 15–36% depending on variety (de Oliviera 1997).
[F] Pollinator reliance from Manning and Boland (2000).
[G] Pollination reliance depends on variety, but low in most cases (McGregor 1976).
[H] Pollinators have a small effect in the field, but are necessary in a greenhouse (McGregor 1976; Kevan *et al.* 1991).
[I] Data from ABS, 1996–97 (Binning *et al.* 2001).
[J] Data from ABS, 1997 (Binning *et al.* 2001).
[K] Data from ABS, 1993–94 (Binning *et al.* 2001).

Varroa destructor had become established in New Zealand, leaving Australia as the last major beekeeping country free of the pest (CSIRO media release, 24 May 2000). The spread of *Varroa* has caused major declines in feral and managed honeybee populations elsewhere in the world. In the US, feral honeybee colonies are now drastically reduced in number (Watanabe 1994), and the number of managed colonies declined 24% between 1995 and late 1996 (Allen-

Wardell *et al.* 1998). Given *Varroa*'s record of spread elsewhere in the world, it seems likely that the mite will eventually reach Australia. A serious quarantine effort has been put in place to forestall this event for as long as possible. This will require very strict control on the importation of honeybees into Australia, and therefore a change in the breeding strategies of beekeepers. If *Varroa destructor* establishes itself in Australia, as it has done elsewhere in the world, we should expect populations of feral and managed honeybees to decline.

Although *Varroa* mite is the most potent threat, the honeybee is also vulnerable to a range of other pests and diseases, including tracheal mites (*Acarapis* spp.) and a range of fungal, viral, protistan, and bacterial diseases (Morse 1978; Shimanuki 1978; Bailey and Ball 1991; Kevan 1999). The vulnerability of *A. mellifera* to disease is associated with its highly social life history. As long as we rely so much on a single pollinator species, pollination services will be vulnerable to disease outbreaks.

Insecticides

Insecticides used to spray crops for insect control also pose a threat to honeybees, which can be killed by many commonly used chemicals (Johansen 1977; Delaplane and Mayer 2000). For example, in spring 1998, drift from aerial spraying with dimethoate in a Western Australian barley crop damaged populations in more than 100 beehives brought in to pollinate canola (Agriculture WA 1998). The conflict between chemical use and insect pollinators requires careful attention to the choice of chemical and the timing and method of application. Managed hives can be moved to avoid insecticide problems, but wild populations of insects are more vulnerable. As a result, excessive or incautious use of insecticides has a negative effect on pollination services. Insecticide drift can also affect native insects and the plants they pollinate, but this phenomenon is little studied (for an exception see Kevan *et al.* 1997).

Even when insecticides do not lead to high bee mortality, they can affect the livelihood of beekeepers. Australian beekeepers gain world market advantage by offering honey that is free of insecticide residues. The use of insecticides introduces the risk of residues appearing in the honey, thereby damaging the beekeeper's primary source of income. Currently, beekeeping in Australia is supported by honey sales, rather than the provision of pollination services (Gill 1989*b*), so declines in the honey market are likely to reduce the level of pollination services available, or lead to increases in the cost of the service.

Genetically modified crops

Recently, there have been increased concerns about the effects of genetically modified (GM) crops on pollinators, although the risks may have been overstated. In the USA, pollen from Bt corn was shown to kill leaf-feeding larvae of the Monarch butterfly in laboratory experiments (Losey *et al.* 1999). In early 2000 there was similar concern about the possible effect of pollen from Bt cotton on honeybees in northern NSW. It transpired, however, that the Bt toxin in this crop was not toxic to bees, and was not expressed in the pollen, thus the threat in this case was non-existent. Nevertheless, pollinators will be vulnerable to genetic modification of plants that renders pollen or nectar toxic to them, and the ecological safety of genetically modified crops needs to be assessed with this in mind.

The significance of threats from GM crops needs to be weighed against the alternative management approach, which currently is the application of insecticides that are also lethal to non-target insects. It is possible that GM crops will benefit pollinators if their use results in less insecticide spray.

The introduction of GM crops could also affect pollination services through a more indirect route. In the same way that beekeepers profit by marketing insecticide-free honey, there is a market for GM-free honey. Therefore, if GM plants grow in or near a pollinator-dependent crop, this might discourage beekeepers from providing their pollination service. GM crops on the horizon include at least 2 widespread bee-visited species: canola and clover.

Loss of remnant vegetation

In Australia, remnant vegetation is important to the maintenance of native pollinators. The role of surrounding vegetation in providing free pollination by native pollinators has been demonstrated for cashew (Heard *et al.* 1990) and *Macadamia* (Heard and Exley 1994). Remnant vegetation is also crucial for the survival of feral populations of *A. mellifera* because it provides hollows for colonies, as well as a diverse array of important food plants. A survey in the Goulburn Valley found that the majority of wild *A. mellifera* nests were in trees, rather than buildings or other artificial structures (Goodman and Hepworth 1996). The role of feral *A. mellifera* in providing free pollination services is potentially great, with 0.8–7.8% (depending on the site) of trees occupied by their nests (Goodman and Hepworth 1996). Clearing of remnant vegetation and dieback of *Eucalyptus* trees threatens the level of service from honeybees. Where there is insufficient remnant vegetation it is unlikely that feral or native bees will provide sufficient pollination to serve agriculture. Native vegetation is also essential to healthy managed hives. Most crops do not provide good quality pollen and nectar resources for honeybees, so hives are maintained in good health on flowering plants found mostly in native vegetation (Gill 1996).

Consequences of pollinator decline in agriculture

There is debate about evidence for a general decline in native pollinators (Matheson *et al.* 1996; Cane and Tepedino 2001).

However, evidence that agricultural pollination is frequently at production limiting levels is unambiguous (Kevan and Phillips 2001). We expect a decline in agricultural pollination to occur due to declining feral honeybee populations, if and when *Varroa* mites arrive. Farmers that currently grow pollinator-dependent crops, but do not provide managed bees, should expect declines in yield or quality. Increasing time from flowering to fruit production in the absence of adequate pollination services will also require increased inputs into crop management. The obvious management response to these problems will be to start paying for pollination services from managed bees. However, managed honeybee populations will also cost more because of the effort required to maintain a disease-free hive. In the USA, beekeepers were leaving the industry at the very time that their pollination services were becoming more valuable (Watanabe 1994). Growers will be forced to compete for the limited services offered by beekeepers, which in turn will become more expensive.

There are few figures available on the degree to which Australian farmers rely on free (i.e. feral) rather than paid (i.e. managed) *A. mellifera* pollination. A survey of growers in the Goulburn Valley found that less than half provided managed bees for their pollinator-dependent crops (Goodman and Hepworth 1996). If one examines the size of pollinator-dependent industries in the Goulburn region (Table 1) it is apparent that a shift to increased managed pollination in the face of declining free pollination would require a great influx of managed beehives.

The increasing cost of pollinators and the possibility that they will be in limited supply might cause some growers to adopt alternative crops, or to move from a relatively low-input production system to a high-input production system where increases in production costs are balanced by increasing the value of the crop. The expansion of pollinator-dependent horticulture will be constrained, however, unless alternative approaches to crop pollination are adopted, or a new and bigger cohort of beekeepers can be attracted to the pollination services sector. Constraints on the expansion of horticulture will in turn affect regional land use and resource decisions, such as water allocation.

The increasing cost of pollination will also lead to an increase in the cost of seeds from pollinator-dependent plants. Demand for pasture seed may increase with declines in *in situ* pollination, and increasing intensification of grazing. Declining seed production by native plants can also create a challenge for organisations that use remnant vegetation as a source of seed to replant native bushland in extensively cleared areas (Mortlock 1999).

Preparing for change

The effects of pollinator decline are substantial, and the risk of decline, particularly after *Varroa* entering Australia, is great. That *Varroa* will enter Australia is a certainty; what remains in doubt is its route of entry. The most likely route of entry is via individuals or feral colonies of *A. mellifera*, either smuggled in or on container ships from countries that have the pest mite (Ritchie *et al.* 2001; NewsRoom media release 2002). A lesser risk is posed by *Apis cerana* arriving from Japan, Korea, or Thailand (D. Anderson, pers. comm.). We are fortunate in Australia, however, to be able to learn from the effect of *Varroa* elsewhere in the world, and to take the opportunity to prepare for the changes that will come with the arrival of this pest. Some changes are essentially behavioural; for example, beekeepers will have to learn new hygiene practices and more growers will have to include pollination services as one of their production costs. Other changes require research, or different approaches to landscape management; these are the issues we focus on here.

Cautious use of insecticides

Insecticide use is an integral part of many production systems, but when insecticides have a negative effect on pollination service there is an additional, usually hidden, cost. It is important that effects on pollinators are considered when choosing an insecticide and when designing an application system (de Oliviera 1997). This is especially true for application during the flowering season in an area with pollinator-dependent crops. Some chemicals are less dangerous to bees than others, and when these are available they should be considered. Where natural enemies are an alternative, these may offer a safer form of control. Timing and method of chemical application are also important in reducing off-site effects, and communicating with local beekeepers can reduce the effect on managed hives. Growers are aware of the need to be cautious when their own crop is flowering, but it is also necessary to avoid having a negative effect on bees in neighbouring crops or remnant vegetation. Because pollination from wild insects is little documented, there is a great risk that the contribution from remnant vegetation will be neglected and suffer the consequences.

Protecting and enhancing remnant vegetation

If Australian agriculturalists want to maintain the free pollination service provided by wild insects, it is important that remnant vegetation is preserved and enhanced. With good management, the natural vegetation that provides food and shelter to *A. mellifera* and native pollinators can be protected. At the same time, fragmented vegetation can be managed to maximise the prospects of sustaining populations of native insects and the plants they pollinate. If growers want to minimise the cost of beekeeping services, there may be value in providing habitat for wild bees around pollinator-dependent crops, in addition to that provided by remnant vegetation. With good planning, plant species can be chosen that would provide a continuous nectar and pollen source, so that bee populations are maximised, and competition for pollinators is reduced. It will also be important to consider the appropriate habitat mosaic that sustains pollinator populations over a broader landscape (Paton 2000). Currently, we know too little about the significance of native insects as crop pollinators to make specific recommendations. More research is needed on the role of native insects in pollinating pollinator-dependent crops, and how that role might be enhanced.

New pollinators for agriculture

An important strategy in preparing for the likely decline in the mite-sensitive honeybee population is to begin developing management practices for alternative species useful for crop pollination (Parker *et al.* 1987; Williams 1995; Cane 1997). Research has shown the potential of non-*Apis* species as commercially managed crop pollinators (Parker *et al.* 1987; Torchio 1987; Free 1993; Richards 1993; Roubik 1995). Indeed, it has been argued that there are good reasons to diversify the range of pollinators used on the basis of inefficiencies in *Apis* alone (Westerkamp and Gottsberger 2000). Because *A. mellifera* is not the most effective pollinator for all crop species, alternative pollinators would in some instances provide an improved pollination service. Manageable pollinators may be found among native insects, or imported from other countries. These options have quite different research and management consequences.

Introducing non-native bees to Australia has considerable and serious risks. There is great concern about the ecological effect of feral bee species already in Australia, such as the long established *A. mellifera*, and the recently arrived *Bombus terrestris* (Hingston and McQuillan 1998, 1999). These introduced species might negatively affect native pollinators or the plants they pollinate (Paton 1993; Hingston and McQuillan 1998, 1999), or become vectors of insect or plant diseases. For these reasons Australia maintains strict quarantine barriers, and the importation of a new pollinator species requires much time, research, and funding. So far only one bee species has been imported into Australia through this quarantine process (I. Peebles, pers. comm.). Since 1973 several attempts have been made by researchers to introduce and establish managed populations of the Alfalfa Leafcutting bee, *Megachile rotundata*, as a specialist pollinator of lucerne (Winn 1989). Interest in this species arose because *A. mellifera* has been considered to be an inefficient pollinator of lucerne, leading to low seed yields. The leafcutting bee was attractive because it has been successfully managed for this purpose in North America since the 1960s. The latest importation program (1997 to the present) has been the most successful in maintaining large populations of bees in the field.

Considerable ecological knowledge is needed to determine the level of risk associated with planned introductions. Foremost is whether or not the insect is likely to establish feral populations outside agricultural areas. Highly adaptable social bees, like *A. mellifera*, have proven to be very successful feral animals. Planned introductions should be restricted to species that cannot become well established outside the managed agricultural environment that they have been introduced to pollinate. Insects with narrow foraging preferences and limiting nesting requirements are likely to be safer than those bees with a broad host range. With the need to be cautious about introduced species, and the necessarily complicated quarantine process involved, future research should more seriously consider the potential of native insects for commercial pollination services.

Specialised pollination systems can be a major barrier to plant domestication, so it is not surprising that most crop species are open to pollination by a wide range of pollinators. Consequently, most crops attract a range of native pollinators when introduced into a new environment. Some of these native pollinators might be candidates for managed crop pollination. For example, in various countries where passionfruit has been cultivated, local species of carpenter bees (*Xylocopa*) visit and pollinate the flowers. However, these bees are rarely abundant enough to maximise fruit set. In Malaysia (Mardan *et al.* 1991), Hawaii (Nishida 1963), and the Caribbean island of St Vincent (Corbet and Willmer 1980), attempts have been made to encourage larger populations of carpenter bees by providing wood for nesting sites. Recent research in Australia suggests that native carpenter bees could also be managed as an alternative to introduced bumble bees for greenhouse pollination (Hogendorn *et al.* 2000).

In Australia the social native stingless bees (Meliponinae) may also be useful pollinators of many crops (Heard 1999; Heard and Dollin 2000). These bees can use artificially constructed hives, and so can be readily moved en-masse. A market already exists for stingless beehives in Australia (Heard and Dollin 2000). Stingless bees also have the added advantage of being effective pollinators of a number of crops. With additional research it will be possible to determine how many different crop species stingless bees can efficiently service. Since their natural geographic range is tropical and subtropical, these bees cannot service temperate agriculture. They may, however, be effective in glasshouses, and have recently been evaluated for glasshouse pollination of capsicums in Australia (Ochiuzzi 1999, 2000).

There are likely to be other candidates for the provision of agricultural pollination in the rich fauna of Australian native bees. In identifying the most promising candidates we need to know more about their biology. Among the most important traits to consider are their propensity to aggregate (so that they can be provided in good number), their willingness to nest in artificial substrates (so that they can be moved to the target crop), and their maximum foraging range (so that the correct number of bees to achieve maximum pollination can be placed on the crop). Currently, we know little about the ecology of most native bees. For some crops, pollination can be improved without the domestication of new pollinator species, but by encouraging existing native flower visitors. Cashew (Heard *et al.* 1990; Heard and Exley 1994) and mango (Anderson *et al.* 1982) have been shown to benefit from pollinators that breed in surrounding bushland.

For some crops, insects other than bees provide good pollination services. Nitidulid beetles are the ancestral pollinators of crop species in the family Annonaceae, which includes custard apple (*Annona squamosa* × *A. cherimola*). When custard apples are grown outside their native range, local species of nitidulids pollinate the flowers in Israel (Gazit *et al.* 1982), in Florida (Nadel and Peña 1994), and in Australia (George *et al.* 1989). Larvae of these beetles breed in decaying fruit and so populations may be enhanced by the provision of breeding sites. Hawkmoths (Sphingidae) are the original pollinators of papaya (*Carica papaya*) (Baker 1976) and will visit the flowers wherever that crop is grown. The most common flower visitors of papaya in Australia belong to the subfamily Macroglossinae (Morrisen *et al.* 2000). The food plants of larval members of this family have been identified as a first step to protecting and enhancing hawkmoth populations.

Conclusions

Varroa destructor is likely to arrive in Australia eventually, and it will have a severe effect on feral and managed populations of *A. mellifera*. A decline in the availability of *A. mellifera* will have significant economic effects on a number of Australia's agricultural and horticultural activities. These industries would be better served if other crop pollinating species were available, but the importation of exotic pollinating species introduces other dangers. Therefore it is critically important that we focus our attention on native pollinators. We need to understand their contribution to agricultural pollination, and understand their ecology as an aid to ensure sustained wild populations. In addition, they offer a resource for the development of new domesticated pollinators.

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