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Final report

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prepared by	Dr Saul A. Cunningham CSIRO Entomology
co-authors/ contributors/ collaborators	David C. Cook and Paul J. De Barro CSIRO Entomology Workneh Ayalew and Solomon Balagawi NARI Papua New Guinea
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Contents

1 Acknowledgments

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This final report does not necessarily reflect the views of all those who contributed.

2 Executive summary

Honeybees (*Apis mellifera*) were introduced to Papua New Guinea (PNG) more than 50 years ago, where they have been managed for their honey and have spawned feral populations. Along with Australia, PNG is one of the few countries in the world where honeybees are not afflicted by the parasitic mite, *Varroa destructor*. However, in 2008 a new parasitic *Varroa* mite was discovered in PNG that was pathogenic to *Apis mellifera* and was therefore considered likely to have an impact similar to *Varroa destructor* that has caused great damage to feral and managed honeybee populations around the world. It was soon realised that this threat might extend beyond honey production to the production of crops that benefit from honeybee pollination. Although some alarming scenarios could be imagined there was insufficient knowledge regarding crop pollination and bee populations in PNG. The goal of this project was to consider the newly emerged threat and develop realistic scenarios that describe possible future impacts on PNG agriculture, based on review of the available literature and consultation with experts on PNG agriculture and beekeeping. Further, our goal was to consider these impacts in economic terms that help prioritise decision making and guide further investment.

We conducted two workshops in PNG to collect and discuss information and formulate possible scenarios. This information was supplemented by the published scientific literature. Economic modelling was conducted using an existing model of *Varroa* spread and impacts, but modified to the particular circumstances in PNG. We also conducted observations of insect visitors to flowering crops at lowland and highland locations to improve our knowledge regarding which bees are acting as potential pollinators.

We concluded the most likely scenario was that impacts of the new *Varroa* would be limited to *Apis mellifera* and therefore geographically limited to the highlands. Losses to agricultural production are expected to be low because dependence on *Apis mellifera* for crop pollination is low. This is because the managed honeybee population is small and rarely used for managed pollination. The feral honeybee population may be large, but nevertheless there are many other wild and feral bee species that are likely to provide a similar crop pollination service (most notably *Apis cerana*) and therefore a decline in one species is unlikely to have significant repercussions. The impact on managed hives would cause damage to honey production and limit opportunities for future development of managed pollination.

This predicted impact was, however, contingent upon a number of assumptions made because of limited local information. Therefore we also estimated the possible impact if honeybee decline were to lead to crop pollination decline (a worst case scenario). We concluded that the largest economic risk is associated with the cash crop, highland coffee. Assuming that the new *Varroa* actually emerged six years ago, and assuming only honeybees are effective pollinators of highland coffee, then we predict mean annual losses of PGK 14.2 million over the next 24 years.

To provide greater certainty around the likely economic impacts of the new mite we suggest more data needs to be gathered regarding the distribution and abundance of feral honeybees, and on the influence of variation in the pollinator community on fruit set by highland coffee in PNG. Further research on coffee pollination would also assist in coping with changes expected due to the mite, and could help coffee growers increase the fraction of their crop sold with a premium for large bean size.

This research has significantly improved our understanding of threats arising from the new mite. This understanding has grown among people in agricultural research, beekeeping and quarantine services. It has been disseminated to the public through press coverage of the issue. Further, the project provided training to a young PNG scientist. The outcomes of this research are likely to influence investment decisions and research in PNG and in Australia where the impact of decline in *Apis mellifera* could be much greater.

3 Background

3.1 The problem

In 2008 a survey of *Apis mellifera* in Papua New Guinea (PNG) detected a new parasite that was identified as a species of *Varroa* mite (Anderson 2008). This mite was found to be pathogenic to *Apis mellifera* (the honeybee), but was not the already well known *Varroa destructor* species that had affected honeybees elsewhere in the world. The newly emerged *Varroa* is a type of *Varroa jacobsoni*, arising from a host switch event, in which it transferred from *Apis cerana to Apis mellifera*. Because this new type of *Varroa jacobsoni* can complete its life cycle on *Apis mellifera* there is a risk that it could be as harmful as *Varroa destructor* has been elsewhere in the world (Anderson 2008). It is not known when it first appeared in PNG but it is likely to have been present since approximately 2003 (Anderson 2008).

3.2 *Apis* and *Varroa* in PNG

Apis species are not native to PNG. Historically, the distribution of the easternmost species finished just west of the island of New Guinea (LeConte & Navajas 2008). The first *Apis mellifera* were introduced in the eastern regions of PNG in the late 1940s (Clinch 1979). The second species, *Apis cerana*, was initially introduced to the Indonesian province of Papua in hived colonies imported from Java in the 1970’s. These produced feral colonies which then spread into PNG in the 1980’s (Anderson 2008). This species remains as a feral in PNG and is not kept as a domestic species. In fact, its presence in PNG makes keeping of domestic *Apis mellifera* more difficult because it raids their hives.

Varroa jacobsoni was originally only a parasite of *Apis cerana*, including the *indica* subspecies (Java type) found in PNG. Until the recent finding in PNG this species was known to be unable to reproduce on *Apis mellifera*, and therefore was not regarded as a direct threat to this species. The related mite, *Varroa destructor*, whose primary host is *Apis cerana*, subspecies *cerana*, is the parasite which, until the recent finding in PNG, was the only *Varroa* known to be capable of reproducing on *Apis mellifera*. Since *Varroa destructor* switched host it has spread around the world causing massive declines of *Apis mellifera* in Europe during the seventies, the US in the eighties and New Zealand since 2000 (Goodwin 2004; Watanabe 1994; Oldroyd 1999). This disease can be managed by beekeepers if they have sufficient expertise and resources, but experience around the world shows that feral *Apis mellifera* populations are dramatically reduced when pathogenic *Varroa* invades.

4 Objectives

The goal of this Small Research Activity is to assess the possible impact of this new bee disease on economic return from PNG crops. A decline in bees could reduce yields for those crop species that depend on insect pollinators, but the size of this effect on the broader economy will depend on the range of crops grown, the degree to which their yield is influenced by pollination (Cunningham 1990), and the net effect of the new disease on the community of insect pollinators. It is expected from the outset that there will be significant knowledge gaps, so this project will also identify the range of uncertainty around projections and identify which areas of new research could help narrow the uncertainty. This will provide information to enable better decisions on pollination by honeybees and the response to the bee mite problem.

This project will not examine the biology of the new disease or its pathogenicity to bees. We will simply assume that its impact on *Apis mellifera* is comparable to that seen elsewhere in the world with *Varroa destructor*.

The specific objectives will be to:

1. Develop future scenarios for the impact of bee mites on pollination, based on uncertain knowledge of the host and geographical range of *Varroa* and of the current contributions of *Apis* to pollination.

Outputs

- Review of available literature on pollination by *Apis* in South East Asia and the Pacific with emphasis on significant crops in PNG.
- Scenario descriptions which can be used for planning future control programs

2. Estimate the potential economic losses and associated ranges (errors) for the crops of highest value within each scenario from objective 1.

Outputs

- Estimates of the value of current and future crop production within the scenario range
- Estimates of the likely reduction in pollination
- Estimates of the range of potential economic impacts

3. To identify knowledge gaps regarding management of this threat to PNG agriculture as the basis for further research

Outputs

- Research questions for the better understanding of;
  - the role of *Apis* in the pollination of PNG crops
  - the threat posed to *Apis* spp by *Varroa*
  - information resources required to undertake future studies on pollinated crop production in PNG

A crosscutting objective will be to enhance the capacity of PNG researchers to undertake these types of studies and to establish new, and strengthen existing collaborative links between PNG and Australian researchers.

5 Methodology, Achievements, Results and Discussion

Because this project is a Small Research Activity, we have combined these sections into an integrated text.

5.1 How could *Varroa* affect PNG agriculture?

Whether or not there is any impact of the new disease on PNG crop production and the size of any possible effects depends on the answers to a number of critical questions. To represent these questions, how they relate to one another and how they affect the net outcome, we have constructed a flow chart (Figure 1). This flow chart identifies three questions (in boxes), each of which are examined in this report. Depending on the answer to each question, the flow chart further identifies three impact scenarios (diamonds) which we will consider. Our initial assessment of the likelihood of each scenario is based on our confidence in the answers to each question.

5.2 Will the disease only affect *Apis mellifera*?

Varroa mites are parasites that feed on the blood of bees and inhabit their hives. To be successful their biology must be tightly matched to the organism they feed on. This matching is selected for by co-evolution (Oldroyd 1999) and there are many ways in which this match in biology must be "just right". For example, for the *Varroa* population to grow in a hive, mites must be able to reproduce on brood bees. As a consequence, the different characteristic types of *Varroa* that have been found so far are species-specific in their impact – i.e. they each only affect one *Apis* species, or even more specifically can only affect a given genotype within that species (Anderson 2008), which is a common pattern for parasites.

Host switches, such as that which gave rise to *Varroa destructor*, and that which appears to have given rise to this new type of *Varroa jacobsoni*, are rare events. For example, *Varroa destructor* on *Apis mellifera* appear to have originated from only 2 individual mites that host-switched from *Apis cerana* (Solignac et al. 2005). These 2 mites were able to successfully colonize *Apis mellifera* simply because they were able to recognize a putative signal on *Apis mellifera* brood that allowed them to produce offspring. Unfortunately for *Apis mellifera*, both mites could reproduce on both drone and worker brood, whereas their mothers could only reproduce on *Apis cerana* drone brood but not on worker brood of *Apis cerana* or *mellifera*, or on *Apis mellifera* drone brood. The new-found ability of the 2 founder *Varroa destructor* mites and their offspring to reproduce on *Apis mellifera* worker brood had led some experts to question whether *Varroa destructor* mites now on *Apis mellifera* may show increased or decreased reproductive ability (and hence more or less harm) when they move back onto *Apis cerana*. This question has not been resolved experimentally. However, it should be noted that one of the two original *Varroa destructor* female mites that first switched host from *Apis cerana* to *Apis mellifera* made that switch in or near Korea, and Korea is the only country where female *Varroa* mites have been reported to be able to reproduce on *Apis cerana* worker brood (De Jong 1988). This suggests that caution should be exercised when making predictions about whether the newly-appeared type of *Varroa* mite in PNG may now have a more serious impact on *Apis cerana* from which it originally switched. Only further research will resolve this issue.

In summary, the newly-appeared type of *Varroa* mite in PNG will most likely have the same species-specific pattern as other *Varroa* species. In the event that it was in fact able to reproduce on two different bee species, then the alternate host would almost certainly be *Apis cerana* from which it originally host-switched, and not any of the non-*Apis* bee species in PNG. A return to *Apis cerana* would only be of relevance to our assessment if its impact was different to that of the original *Varroa jacobsoni* (i.e. the mother of the new species) which is already on this host. Such an event, (i.e. a second host switch, plus increased pathogenicity) can be considered unlikely, but some observations on *Varroa* biology suggest it is possible.

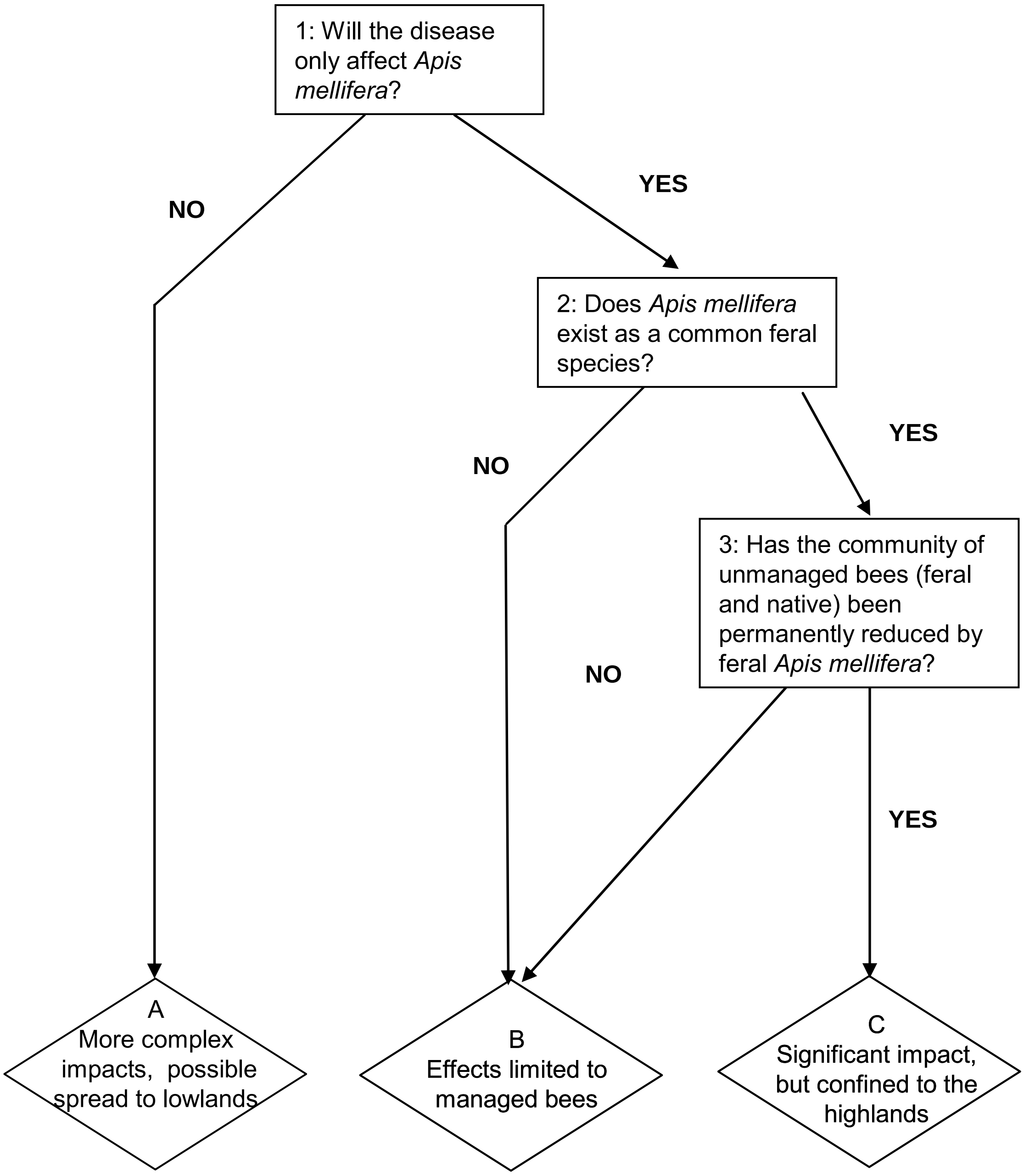


Figure 1: Flowchart describing the key questions regarding the likely impact of the new Varroa, and how they relate to likely impact scenarios.

5.3 Does *Apis mellifera* exist as a common feral species?

If *Apis mellifera* has not established as a common feral, then the only impact of the new *Varroa* disease will be on the managed *Apis mellifera* population (scenario B). If, however, there is a significant feral *Apis mellifera* population, then the impact will be greater.

Feral honeybees have the potential to be very widespread and to act as effective crop pollinators without any human intervention – in fact feral honeybees in Australia are thought to be responsible for a much greater fraction of pollination than that achieved by managed bees (Cunningham et al. 2002). We have been unable to uncover quantitative data on the abundance of feral *Apis mellifera* in PNG. However, the scientific literature suggests that feral bees successfully spread into the PNG highlands after their introduction in the late 1940's (Clinch 1979; Michener 1963). Further, *Apis mellifera* has been a very adaptable and successful invasive species elsewhere in the world, establishing virtually anywhere that the climate is suitable, such as it is in much of highland PNG (Anderson 2008, and see comments in (Michener 1963). This history leads one to expect that the establishment and spread of feral *Apis mellifera* from managed hives was inevitable. However, it is expected that feral *Apis mellifera* will not establish a permanent presence in lowland PNG because the hotter climate does not suit them (Anderson 2008).

There is indirect evidence for the presence of widespread feral *Apis mellifera* from the pattern of *Tropilaelaps* invasion. *Tropilaelaps* is another host-specific mite that reproduces on *Apis mellifera*. It spread from the Indonesian province of Papua into the highlands of PNG in spite of the fact that there are very few domestic *Apis mellifera* in the region on the PNG side of the border (Denis Anderson pers. comm.). This spread was most likely facilitated by widespread feral *Apis mellifera* in the region. Further, Denis Anderson has seen feral bees in the eastern highlands of PNG during his field trips (pers comm.) One of the world's foremost bee experts, Charles Michener, collected observations from colleagues in what was then Australian New Guinea, and from these observations suggested that *Apis mellifera* was well established in PNG in the 1960's, suggesting that they occupy an area 'over 250 miles long in the central part of the Territory of New Guinea' (Michener 1963; Michener 1964).

Although the data is largely anecdotal or inferential, we suggest that *Apis mellifera* is well established as a feral species in highland PNG, but is unlikely to establish permanent populations in the lowlands.

5.4 Has the community of unmanaged bees (ferals and natives) been permanently reduced by feral *Apis mellifera*?

Given that the total population of managed *Apis mellifera* hives is relatively small, crop pollination must have been achieved historically by the native insect community (especially native bees), in more recent years with help from feral *Apis* species (*cerana* and *mellifera*). The loss of feral *Apis mellifera* to disease might diminish the community of unmanaged pollinators in a way that reduces this free pollination service, but the remaining bee community might continue to provide an ample service unless the community of unmanaged bees (natives plus the feral *Apis cerana*) has been permanently reduced by feral *Apis mellifera*.

If *Apis mellifera* has not had a lasting impact on the community of unmanaged (i.e. wild) bees, then the impact of declining *Apis mellifera* will be small (scenario B). If, however, *Apis mellifera* has had a lasting impact, then the level of crop pollination that can be provided by this free ecosystem service will diminish to a lower level than it has been for decades, since the time before the expansion of *Apis mellifera* (scenario C). Unfortunately, there are no PNG specific data on this matter and in fact little data worldwide on the resilience of bee communities to the impact of *Apis mellifera*.

At the heart of this is the question of whether *Apis mellifera* has a history of driving other competing pollinators to extinction. Species extinction means the species is lost from the system, whereas if species are simply suppressed by competition, then one expects them to return to previous levels after the major competitor is removed, thus providing resilience in the community level response. The issue of suppression versus extinction has been the focus of considerable attention in Australia (Butz Huryn 1997; Manning 1997; Paton 1993; Paton 1997; Paton 1996; Roubik 2002b), where *Apis mellifera* has been such a successful and well entrenched feral species (Oldroyd et al. 1994). There have been numerous studies from around the world showing that when honeybees are present, native bee visitation rates are reduced. Unfortunately, this research does not answer the fundamental question regarding the long term survival of these native species in response to honeybee competition. Only by looking at reproduction, survival, or population levels can one really answer this question (Paini 2004). Recently researchers have focused on the reproduction of native bees when honeybees are present. Two studies, one of which was conducted in Australia, show a negative impact of *Apis mellifera* on natives (Thomson 2004; Paini & Roberts 2005) and two others found no impact (Paini et al. 2005; Spessa 1999). In other words, the scientific literature shows negative impacts of honeybees in some cases, but also that negative effects will not be felt in all sites at all times. Indeed some studies suggest that in some cases, particularly when nectar is very abundant, competition between *Apis mellifera* and native fauna is low (Paton 1999). Further, while some studies show that feral *Apis* might have a negative impact on other pollinators when they are in competition, there are no studies that establish whether or not this competition effect persists after removal of *Apis mellifera*. This latter point is in fact the most important in predicting the future for pollination in PNG.

In the PNG highlands one of the wild bee species likely to effectively pollinate crops is feral *Apis cerana*. The fact that *Apis cerana* spread into PNG after *Apis mellifera* suggests that this species is not strongly suppressed by feral *Apis mellifera*, and that it can in fact prosper in similar environments and at the same time as *Apis mellifera*. One could predict then that *Apis cerana* will continue to prosper whether *Apis mellifera* is present or not, and that this species has the potential to provide a significant ongoing unmanaged pollination service.

Relations between plants and their pollinators have been found to be generally asymmetrical, meaning that if a plant depends strongly on one pollinator, that pollinator typically depends only weakly on that plant (Vazquez & Aizen 2004; Bascompte et al. 2006). This pattern provides stability in the face of perturbations because species declines will not generally lead to cascading changes. Because most plant-pollinator relationships are not highly specialised, introduced species tend to be easily accommodated into new plant-pollinator communities (Memmott & Waser 2002). Alien species can nevertheless change the structure of invaded webs, especially when the invaders are adaptable and social, such as *Apis mellifera* (Aizen et al. 2008). It is not the case that *Apis mellifera* can only pollinate species from its original native range in Africa and Europe, nor is it the case that crops of African origin (such as *Coffea arabica*) can only be pollinated by African pollinators. There are abundant examples of crops being effectively pollinated by insects that did not occur in the plant's original native range. The fact that *Apis mellifera* is an effective pollinator of so many plants worldwide (Klein et al. 2007) is testimony to its flexibility in visiting and pollinating plants that it has only recently (in evolutionary history) encountered. There is no reason to assume that a growing dependence on introduced agricultural crops will necessitate a growing dependence on introduced pollinators, but in contrast changes in land management might affect the capacity of the wild pollinator community to deliver the service of crop pollination.

Not all bees are expected to provide the same level of crop pollination. Crop pollination differs from the pollination of many native species in that the plants are arranged in high density patches, in environments that have been highly modified by humans, usually by clearing woody vegetation and simplifying the structural complexity of the environment. In the extreme case, humans plant large areas (>100 ha) of one synchronously flowering species, in a landscape with little other vegetation or structural complexity – such is the case for canola cropping in south-eastern Australia, for example. This means that a high density of flowers appears for a short period of time in an environment that offers few other resources for pollinators. Pollinator nesting habitat is often only found outside the field, which means a flight of hundreds of meters to access flowers in the middle of the field. As a consequence, the availability of pollinators in these systems has been found to decline with distance from the field edge and with distance from woody vegetation (Arthur et al. in review). Indeed the pattern of declining visitation and pollination with increasing distance from non-crop vegetation is quite general across many studies (Ricketts et al. 2008). *Apis mellifera* is viewed by many as a good crop pollinator because it will fly long distances and will recruit other workers from the hive to abundant flower resources (Beekman & Ratnieks 2000), therefore making it relatively effective at servicing high flower densities that cover larger continuous areas. *Apis cerana* has been the subject of less research, but shares many of the same traits that make *Apis mellifera* a good crop pollinator.

Agriculture in the highlands of PNG, however, is not dominated by large areas of monocultural plantings in a structurally simplified environment. Rather it consists mostly of small patches of a high diversity of crops and trees that creates a landscape with high spatial, structural, and phenological diversity and a relatively fine “grain” (i.e. average patch size). This is the kind of environment that we expect to support a diverse and widespread wild pollinator community (including ferals) and which is less likely to suffer from crop pollination shortages. The relative advantage that feral *Apis mellifera* have over the rest of the bee community in other landscapes are likely to be diminished in this type of landscape. Nevertheless, parts of highland PNG have been cleared of large trees. Tree hollows, which are more common in older trees, are a crucial nesting resource for many social bee species, including *Apis* species (Oldroyd et al. 1994). Areas where tree hollows are very few might be expected to have lower wild bee density, with relatively fewer social bees and more solitary bee species. Further, PNG agriculture is constantly changing. Although agriculture has a very long history in PNG (it being one of the centres in which agriculture first evolved) many of the currently important crops are relatively recently introduced and agricultural methods are not fixed in time. But it is more important in this case to look forward towards future options for agriculture and land management, rather than to look to the past. Any trend towards more homogenous or broadscale monocultural approaches to agriculture would put greater pressure on the wild pollinator community, making it less likely that they can provide sufficient pollination services.

We predict that the unmanaged bee community, consisting of feral *Apis cerana* and a diversity of native bees, may have been affected by the presence of feral *Apis mellifera*, but it is most likely that the community would respond to the loss of *Apis mellifera* in a way that at least partially compensates for the loss of service from this one species. There are insufficient data to predict whether this compensation will be partial or complete. It is even possible that there could be overcompensation in the pollination rate for some crops, if *Apis mellifera* has been suppressing the abundance of more efficient pollinator. Of the species in the remaining unmanaged bee community, *Apis cerana* is likely to be particularly important because it shares with *mellifera* the ability to sustain large populations of individuals, flexible foraging behaviour, and a relatively large body. If *Apis cerana* were lost also then there is a much greater probability that the crop pollination service provided by the remaining community could be diminished.

5.5 Impact scenarios

Having identified possible impact scenarios (Figure 1) that result from the answers to the three main questions, we now examine the risks associated with each. We consider both the likelihood and the expected consequence.

5.5.1 Scenario A: Complex impacts, *Varroa* spreads to the lowlands

The only route to this outcome is through the new *Varroa* disease having an impact on *Apis cerana* as well as *Apis mellifera*. As discussed (Q 1) this is considered very unlikely, but not impossible. Given the great uncertainty around this it is difficult to develop an informative model. The most important feature of this scenario, relative to scenario C, is that the potential impact on crop yields spreads beyond the range of *Apis mellifera* (i.e. the highlands) down into the lowlands. By virtue of spreading into the lowlands, a whole different suite of crops would be exposed to a change in the pollinator community. To understand the size of this potential impact one would need to know how important *Apis* *cerana* has been as a crop pollinator for lowland crops, and whether or not the wild pollinator community would show resilience if *Apis cerana* was lost.

5.5.2 Scenario B: Effects limited to managed bees

This scenario arises when the impact is limited to managed *Apis mellifera*; either because the feral *Apis mellifera* population is trivial, or because the loss of feral *Apis mellifera* is largely compensated by resilience in the unmanaged bee community. We suggest that the latter (i.e. resilience) is likely and so this scenario is the most likely of the three.

There are currently only about 4000 *Apis mellifera* hives among 500 small holders (Anderson 2008). Some beekeepers in some locations get payment for pollination services, such as from some of the larger plantation coffee producers in Mt Hagen (Anderson pers. comm.). However, there are currently too few hives to provide a pollination impact on an industry-wide scale. To illustrate this problem, consider the situation for coffee. There were 70,000 ha of coffee harvested in 2007 (FAO). The recommended density of hives in coffee is approximately one hive per ha (Agriculture WA) therefore, if all the hives in PNG were applied to this one crop they could still only serve about 6% of the planted area.

In summary, because there are relatively few beekeepers in PNG and because they are not strongly engaged in the provision of crop pollination services, the loss of managed honeybees would have only a small effect on current agricultural practice. The loss of managed honeybees would, however, have a direct impact on people engaged in beekeeping and on honey production. Further, loss of beekeepers represents a lost opportunity. For example, managed pollination can increase coffee value by increasing the bean size and timing of production. Currently A and AA grade coffee only represents only 9% of the market (Batt 2008), but with changes to the industry this fraction could be increased, and managed pollination could be an important part of the improved management practices required.

5.5.3 Scenario C: Yield declines, confined to the highlands

This scenario arises when there is a loss of managed *Apis mellifera* which is not compensated for by the remaining native bees or feral *Apis cerana*. Because the *Varroa* impact is confined to *Apis mellifera*, the agricultural zone affected is limited to the highlands. As already argued, loss of managed bees would be only a very small part of the effect. The more significant impact comes from the loss of feral *Apis mellifera*. Because of the absence of locally relevant information, it is difficult to be precise about the likelihood of this impact, or of the size of the consequences. However, we expect that pollination from the community of unmanaged bees will be resilient (as argued above) and at least partially compensate for loss of *Apis mellifera*. Nevertheless, to establish what this plausible and potentially important impact could be, it is necessary to consider what would happen if the loss of feral *Apis mellifera* did lead to diminished crop pollination. To this end, we identify first which crop species could be affected, and second we explore economic models that estimate the size of the impact.

5.6 Important PNG crops that depend on insect pollination

The majority of plant species require insect pollination to achieve maximum reproductive success. Domestic crops are no different in this respect, with the majority of species benefiting from insect pollination (Klein et al. 2007). However, many important crops reproduce vegetatively (e.g. sweet potato, yam) or are mostly wind pollinated (especially grasses like maize and rice). Other crop species require pollination to make seed, but do not require pollination to produce the part we eat (e.g. carrots or leaf vegetables). In this section we focus only on those crop species in which insect pollination is linked to the yield of the part that is harvested. We refer to these species as “benefitting from insect pollination”.

We reviewed the literature to identify crops that are widely grown in PNG and which are known to benefit from pollination. Here we separate these crops into those grown for different purposes, and further whether they are grown in the highlands or lowlands. The primary resource for this review is the extensive literature compiled by Bourke and Harwood (2009).

5.7 Staples, fruits and vegetables

Most of the staple crops (Allen et al. 2001) do not benefit from insect pollination. The only common staple which benefits from insect pollination is the coconut (Melendez-Ramirez et al. 2004) which is important in terms of its contribution toward calories consumed by rural people, being second only to sweet potato, at 10.9% (Allen et al. 2001). Coconut is grown mostly in lowland provinces and therefore would be unaffected by changes in the bee community of the highlands.

Fruits and vegetables are important both to the home diet and the local trading economy (Bourke and Harwood 2009). Here we focus on the most important village crops according to Bourke and Harwood (2009) and establish whether they benefit from pollination (Table 1). To construct the table we included four categories of crops:

- the 10 most important fruits, as listed by Bourke and Harwood (2009)
- the 16 most important nuts, as listed by Bourke and Harwood (2009),
- the one staple crop known to benefit from insect pollination (coconut),
- those vegetables in Bourke and Harwood's (2009) 16 most important which are fruits or seeds (rather than roots, leaves or stems) and therefore might be influenced by pollination

To classify the degree of dependence on pollinators we reviewed the literature, and then used the categorisation adopted by Klein et al. (2007) (i.e. "Essential" >90%, "Great" 40-89, "Modest" 10-39%, "Little' some evidence of an insect benefit but <10%, "No increase" 0, "Unknown" insufficient appropriate empirical studies).

Table 1 Pollination dependence of important PNG fruit or seed crops (not including cash crops). Altitudinal range is based on the reported patterns of planting by province (Bourke and Harwood 2009), with only Southern Highlands, Enga, Western Highlands, Simbu and Eastern Highlands regarded as high.

Food Category	Common name	Species name	Pollination dependence	Altitudinal range	References and notes
Staple	Coconut	*Cocos nucifera*	modest	low	(Melendez-Ramirez et al. 2004)
Vegetable	Cucumber	*Cucumis melo*	great	high & low	(Klein et al. 2007)
Vegetable	Snake bean	*Vigna unguiculata*	little	low	(Vaz et al. 1998)
Vegetable	Winged bean	*Psophocarpus tetragonolobus*	little	high & low	(Sastrapradja et al. 1980)
Vegetable	Corn, Maize	*Zea mays*	none	high & low	extensive evidence of efficient wind pollination
Vegetable	Common bean	*Phaseolus spp.*	little	mostly high	(Klein et al. 2007)
Vegetable	Peanut	*Arachis hypogea*	little	high & low	(Blanche et al. 2006)
Fruit	Pawpaw	*Carica papaya*	little	high & low	(Klein et al. 2007)
Fruit	Marita pandanus	*Pandanus conoideus*	none	high & low	(Cox 1990)
Nut	Karuka	*Pandanus jiulianetti & brosimos*	none	mostly high	(Cox 1990)

Fruit	Pineapple	*Ananas comosus*	none	high & low	(Westerkamp & Gottsberger 2000)
Fruit	Mango	*Mangifera indica*	great	low	(Klein et al. 2007)
Fruit	Watermelon	*Citrillus lanatus*	essential	low	(Klein et al. 2007)
Fruit	Ton	*Pometia pinnata*	unknown	low	No data
Fruit	Malay apple	*Syzygium malaccense*	unknown	low	many bee visitors (Falcao et al. 2002) and bat visitors (Start & Marshall 1976)
Fruit	Guava	*Psidium guajava*	modest	low	(Klein et al. 2007)
Fruit	Orange	*Citrus x sinensis*	little to modest	low	(Klein et al. 2007; Malerbo-Souza et al. 2003)
Fruit	Passion fruit	*Passiflora edulis*	essential	high & low	(Klein et al. 2007)
Nut	Breadfruit	*Artocarpus altilis*	unknown	mostly low	seedless varieties need no pollination
Nut	Tulip	*Gnetum gnemon*	unknown	low	probably insect pollinated, (Kato et al. 1995)
Nut	Sea almond (Talis)	*Terminalia catappa*	unknown	low	insect pollination appears to be important for some *Terminalia* spp (Srivastava 1993)
Nut	Okari	*Terminalia kaernbachii, T. impediens*	unknown	low	as above
Nut	Dausia	*Terminalia megalocarpa*	unknown	low	as above
Nut	Castanopsis	*Castanopsis acuminatissima*	unknown	high	probably insect pollinated, (Kaul et al. 1986)
Nut	Pao	*Barringtonia procera*	unknown	low	No data
Nut	Sis (Solomon)	*Pangium edule*	unknown	mostly low	No data
Nut	Galip	*Canarium ovatum*	unknown	low	No data
Nut	Polynesian chestnut (alia)	*Inocarpus fagifer*	unknown	low	No data

There are a wide range of species grown that benefit from insect pollination, and a number for which there is little or no data (Table 1) this is especially true for the indigenous crops. Of the species known to have moderate or greater dependence on pollination, only two are grown in the highlands, these are cucumber and passion fruit.

In summary, the most import crops in terms of calories and in local trade (the staples) are not vulnerable to *Varroa* impacts. Coconut would be vulnerable if decline in pollination were to spread to the lowlands. Because coconut is a cash crop as well as a staple, we discuss this case further in the cash crop section below. There are a few fruit and vegetable crops that could be exposed to pollinator decline in the highlands, and a few more that would be affected if pollination decline also afflicted the lowlands. However, these crops are part of a diverse list of species that are grown in mixtures that vary by location. There could be economic impacts of yield declines but they would be diffusely spread. There would be potential for people to adjust through substitution with other crops, just as there has been ongoing change in the list of exotic species included in local agriculture. In summary, although there is potential for economic impact we believe that these impacts would be very small in comparison to the potential impact of a decline in cash crop production, and that the potential to accommodate change will be relatively greater.

5.8 Cash crops

Cash crops are important in terms of providing money for health and education, but also in terms of buying food for family consumption (Allen et al. 2009). To summarise the scope for pollination to effect cash crop production we used data from Allen et al (2001) that records the income to rural people from cash crops, and then recorded which of these products benefit from pollination (Table 2). Five of the six most important cash crops in terms of income for rural people benefit in some way from pollination. This startling fact emphasises the role that the ecosystem service of crop pollination has in the PNG economy. However, if *Varroa* impacts are restricted to the highlands of PNG, then only one of these crops is potentially vulnerable to the impact of *Varroa*: Arabica coffee. Coconut, oil palm and cocoa are lowland crops, and cocoa and oil palm are known to benefit mostly from non-bee pollinators. Although some fresh foods benefit from pollinators, the most important fresh food trade in the highlands is in sweet potato, which is invulnerable to pollinator decline. The betelnut palm is an important cash crop (although for domestic consumption) grown mostly in the lowlands. We have recorded it as not dependent on pollinators, though this is based on only one small study (Murthy 1977). Further research is necessary to be more confident in our assessment of its reliance on pollinators.

Nevertheless, the one cash crop that could be affected by *Varroa* also happens to be the cash crop that provides the greatest proportion of income to rural people (Table 2). This is because it combines high returns per person with being grown by a large percentage of the rural population. Oil palm is significant in term of the national economy and has shown strong growth in recent decades (Figure 2). This species is grown exclusively in the lowlands, and so is invulnerable to changes affecting only *Apis mellifera*. Although the economic returns are high, they are also concentrated in the hands of relatively fewer people than is the case for coffee. This is partly because the lowlands are less heavily populated, but also because more of the oil palm estate is in large managed plantations, whereas most coffee production is in the hands of small-holders. It is known that the best pollinator of oil palm is a weevil (Westerkamp and Gottsberger 2000) which has been introduced into Asian oil palm plantations to improve yield. Therefore pollination management in oil palms might be best achieved by non-bee pollinators.

Because of the great importance of Arabica coffee as a cash crop, and its potential vulnerability to a decline in pollination, we collected some more specific information on coffee pollination.

Table 2 Estimated cash income from agricultural sources, for people in rural PNG, 1996, and the extent to which there is a link to insect pollination (income data from Allen et al (2001).

Product	Benefits from pollination?	% total income	% total population[5]	Average income per person (PGK)
Arabica coffee	Yes	33.3	12.0	43
Fresh food	Some crops[1]	20.3	24.7	13
Cocoa	Yes[2]	11.3	6.5	27
Betelnut and pepper	No[3]	9.5	9.8	15
Coconut and copra	Yes	8.6	4.5	30
Oil palm	Yes[4]	3.4	1.0	53
Fresh fish and shellfish	No	2.4	4.4	8
Firewood	No	2.3	8.2	4
Irish potato	No	1.7	4.6	6
Tobacco	No	1.7	5.5	5
All other products	NA	1.4	3.9	6
Cattle	No	1.2	4.3	4
Robusta coffee	Yes	1.1	3.0	5

Crocodile	No	0.6	2.1	4
Pelt and plumes	No	0.5	1.5	5
Rubber	No	0.4	1.1	6
Pyrethrum	No	0.4	1.0	6
Cardamom	Yes	0.1	1.1	1
Chillies	Yes	0.1	0.8	2
Rice	No	0.0	0.0	5

[1] Some fresh food crops benefit from insect pollination (Table 1), however the largest fraction of the fresh food market is in staples that do not require pollination, especially sweet potato
[2] Cocoa is pollinated almost exclusively by midges – so there is no role for an interaction with bees

[3] There it is limited data, but it suggests that wind pollination provides sufficient fruit set (Murthy 1977)
[4] Oil palm is most effectively pollinated by a weevil (Westerkamp and Gottsberger 2000)
[5] Because people may have more than one major source of cash income, hence the total population given here exceeds the actual rural population.

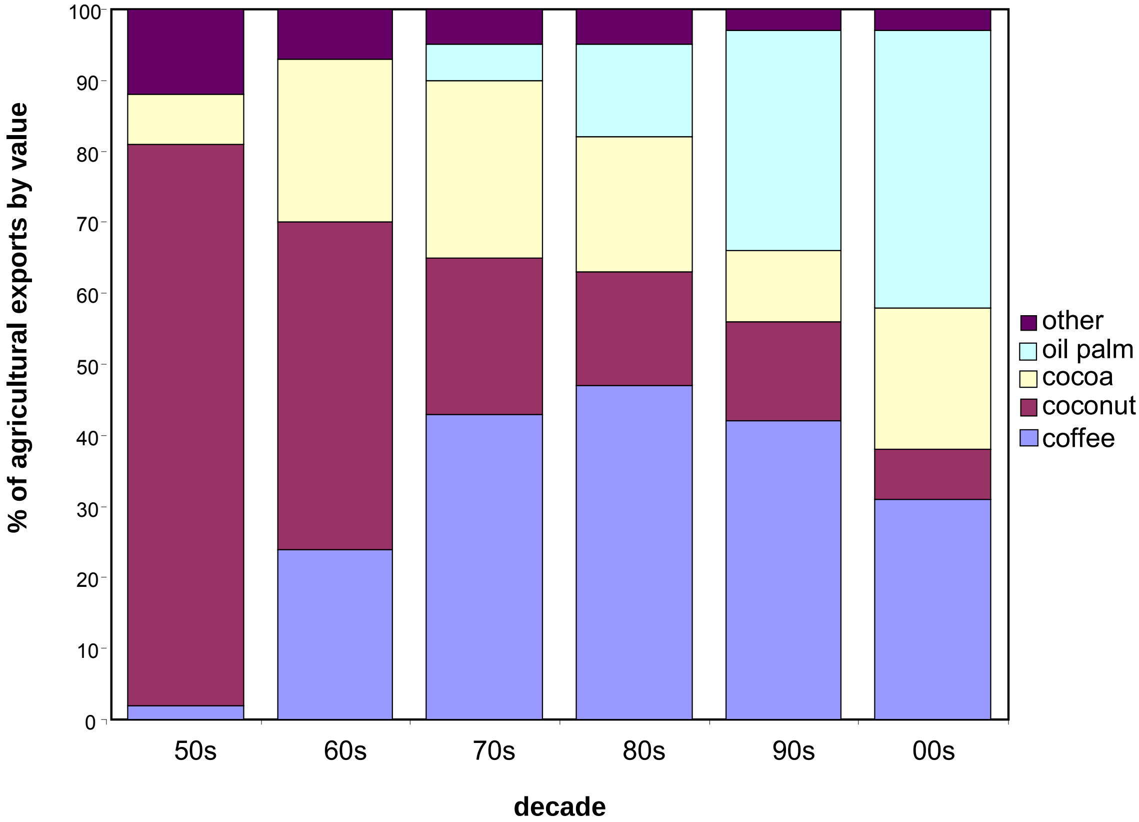


Figure 2 The percentage value of all agricultural exports for major products from the 1950's to the present. This figure is derived from data presented in (Allen et al. 2009). The decade of the 2000s includes data up to 2006.

5.8.1 Coffee pollination

There has been one study of coffee pollination in PNG published in the international science literature (Willmer and Stone 1989), however it focused on lowland coffee which in PNG is a minor crop compared with *Coffea arabica*. This species also differs from *arabica* in being self incompatible, and therefore even more dependant on insect pollinators (Klein et al. 2003a). Interestingly this study found that the predominant pollinators were native solitary bees that were nesting within the plantation.

Pollination of Arabica coffee (*Coffea arabica*) has been well studied worldwide, although none of the peer reviewed research has been conducted in PNG. We reviewed this literature and recorded the impact on the quantity and quality of coffee estimated by experiments designed to quantify insect pollination. Considering data from 8 different studies, insect exclusion can reduce the number of coffee fruits (sometimes called beans or cherries) by 10 to 21% (Table 3). Similar studies show that in addition to a decline in the number of fruit, there can be a decline in mass per fruit. We found data for 3 studies, with impacts ranging from 15-25% (Table 3). Ricketts et al. (2004) also noted that there were 27% less “peaberries” (i.e. very small fruit) when bees were present, which is consistent with the range of effects on fruit mass that we record, though not expressed in precise mass terms.

There are a number of contributors to the relatively wide variation in estimates of pollinator benefit. While some error is introduced by differences in experimental approaches, it is well known that real differences exist among the different varieties of coffee grown, and further that the size of the benefit depends on the abundance and identity of pollinators in the experimental system (Klein et al. 2008). One could develop a more precise estimate of the likely benefit of coffee pollinators in PNG by conducting simple experiments in PNG locations.

In terms of the effect that pollinating insects have on coffee yield in mass per area both the effect on fruit number and the effect on fruit mass are relevant. To estimate the lower bound of the effect of pollinators on coffee yield we combined the low value for number and the low value for mass, giving a net effect of 27%. To estimate the upper bound of the effect of pollinators on coffee yield we combined the high value for number and the high value for mass, for a net effect of 51%.

A few studies published in small non-English language journals more than 30 years ago have been cited for more data on pollinator impact on coffee yield. We have not included these because they are difficult to validate, and in some cases references to these data are unclear on the matter of whether or not they detect the combined effect of number and mass effects, or effects on number only. One source that is sometimes cited for high impact of pollination is Roubik (2002b). This paper, however, presents no new data but simply refers back to Roubik (2002a). Our review of this paper suggests that the often cited figure of approximately 50% effects on coffee yield should be considered the net effect of fruit number and fruit mass effects, and are therefore consistent with the upper bound of our range. It is also important to note that two errors occur in Roubik (2002b); first he reported FAO data on worldwide coffee yields but incorrectly translated the units, secondly he stated that *Apis mellifera* are not present in PNG.

Table 3 Estimates of the yield benefit provided by insects to Arabica coffee fruit production

Fruit per flower increase (%)	Source
10	Manrique & Thimann (2002)
12	Klein et al. (2003a)
14	Amaral (1972), described in Manrique & Thimann (2002)
16	Badilla & Ramirez (1991)
17	Sein (1959) described in Free (1993)
17	Roubik (2002a)
21	Ricketts et al. (2004)
21	Amaral data described in Free (1993)
Fruit mass increase (%)	
25	Roubik (2002a)
22	Manrique & Thimann (2002)
15	Calculated from Raw & Free data presented in Free (1993)

Although the number and mass effects jointly contribute to yield, the mass effect can also have an additional effect on quality. Bean size is one of the factors determining the market price for coffee, with bigger beans having a higher value. It is possible, therefore, that optimal pollination can not only increase the quantity of coffee produced, but also the market price per unit.

Studies from southeast Asia and South America show that coffee is often grown in a manner that encourages diverse pollinator communities, providing benefits to fruit set (Klein et al. 2003b; Klein et al. 2002; Klein et al. 2008; Vergara & Badano 2009). Contributing to this is the fact that coffee is often grown under a canopy of trees, and often in small plots in heterogeneous environments. These patterns are likely to be true for much of PNG's coffee production also. Such was certainly true for in the study of lowland coffee pollination in PNG (Willmer and Stone 1989).

Coffee production in PNG began in earnest in the 1950's, with exports exceeding 40,000 tonnes per year from the late 1970's (Bourke and Harwood 2009). Therefore coffee plantations were developing at approximately the same time that Michener observed that feral *Apis mellifera* were widespread in the highlands (Michener 1963; Michener 1964) but before *Apis cerana* invaded PNG. Unfortunately it is not known how important *Apis* have been as coffee pollinators in PNG, although given observations elsewhere in the world it is expected that *Apis* would be a frequent visitor to any coffee flowers found with their foraging range. There has been an important land use change of the last 30 years such that coffee production was earlier dominated by large plantations but a large fraction is now coffee produced by small-holders (Allen et al 2009).

5.9 Modelling economic impact of *Varroa* on highland coffee

We focused our economic assessment on the case of Arabica coffee production in the highlands. We focus on this case because we believe the impact of *Varroa* is unlikely to extend beyond the highlands, and that among the highland crops that could be vulnerable to pollinator decline Arabica coffee is overwhelmingly the most important.

We use a bioeconomic model developed in Cook et al. (2007) adapted for the PNG case. The objective of the model is to assess the significance of the threat posed by *Varroa* by simulating its total expected (or probability-weighted) damage over a specified period of time (30 years). The use of random number generators to simulate chance or random events is common in risk analyses modelling natural systems with high parameter uncertainty and variability. This is the approach used here. Parameters are stated within an abstract model as probability distributions rather than point estimates, and a Monte Carlo algorithm used to sample from each of these distributions (Cook & Matheson 2008).

To summarize the Cook et al. (2007) model, production loss per unit of land area (d), spread area (A), population density (N) and the number of satellite sites in each time period (St) are combined with the probability of entry and establishment (p) in an expression of probability-weighted, or expected damage over time. Since the new *Varroa* has been present in PNG for some time, we treat p = 1. However, we simulate its spread from the time the first viable population became established (i.e. approximately 2003 (Anderson 2008)). Given a discount rate α, the present value of expected damage after n time periods (PV(EDn), Cook et al. 2007) is:

$$\mathrm{PV}(\mathrm{ED}_{\mathrm{n}}) = \sum_{\mathrm{t}=0}^{\mathrm{n}} (1+\alpha)^{-\mathrm{t}} . \sum_{\mathrm{j}=1}^{s_{\mathrm{t}}} p.d.A.N \qquad (1)$$

Discounting is used because a dollar available for investment in the present is more valuable than a dollar that will not become available until a later period. The future dollar has an opportunity cost associated with it (i.e. investment opportunities we have had to forgo while we wait for it to become available for spending). The expression in (1) provides a probability-weighted estimate of *Varroa*-induced revenue losses in coffee crops in present value terms. It is a measure of expected damage taking into account uncertainty in the severity of production effects, and change in abundance and distribution of *Varroa* over time.

The spread module of the model is unchanged from Cook et al. (2007), reflecting the view (explained above) that the newly discovered *Varroa* is likely to exhibit the same behaviour as *Varroa destructor*. This spread function was informed by data from Harris and Harbo (2001). The host description has been changed to reflect the circumstances of coffee production in the Highlands of PNG. Impact is simulated across the six production regions the Eastern Highlands (accounting for 41% of the country's coffee production), the Western Highlands (41%), Morobe (6%), Simbu (4%), Enga (4%) and the Southern Highlands (2%) (Bourke and Harwood 2009). Using these percentage contributions to total coffee output and estimates of total nation Gross Value of Production (GVP) (i.e. price × total volume produced, taken from Bourke and Harwood 2009) we calculated the area planted to coffee in each region. Table 4 provides estimates of area planted ± 10% to reflect uncertainty in the data.

Table 4 Estimated PNG coffee production area and gross value 2008/09

Region	Area (Ha)	GVP (PGK)
Western Highlands	37,310 ± 3,690	128,385,700
Eastern Highlands	37,310 ± 3,690	128,385,700
Morobe	5,460 ± 540	18,788,100
Simbu	5,460 ± 540	18,788,100
Enga	3,640 ± 360	12,525,400
Southern Highlands	1,820 ± 180	6,262,700
TOTAL	91,000 ± 9,000	313,135,700

For those areas affected by *Varroa* (that is, areas experiencing a decline in pollination by *Apis mellifera*) there is assumed to be no option other than to accept a yield loss. As the PNG beekeeping community is too small to bridge the gap created by a loss of feral *Apis mellifera*, we simply assume a yield loss will be felt in terms of yield in mass terms. We accept that there is also likely to be a loss of quality associated with a loss of honeybee pollination which could lead to the downgrading of premium coffee harvests. However, given that most PNG coffee is graded at relatively low levels and only a small proportion (i.e. 9%) attracts an A or AA quality rating (and corresponding price) (Batt 2008) we have not included a quality effect in the model.

Our review of the literature shows that the effect of insect pollination on coffee yield fruit ranges from 27 to 51%. We specify total yield loss as a uniform distribution with a minimum value of 25% and a maximum of 52% (i.e. UNIFORM (0.25, 0.52). This small difference in range between the data from the literature review and the modelled range reflects the fact that extra data was found in the literature review after the economic modelling was complete, however the difference is very small.

These numbers represent likely decline if all insect pollination ceased, so is almost certainly an over-estimate of yield losses. If other pollinators continue to provide pollination services to coffee crops in the presence of *Varroa* the decline in fruit set and bean mass will be less than we have assumed.

Assumptions underpinning the biological module of the model are provided in Table 5. Growth in the number of affected crops is assumed to follow a Verhulst-Pearl logistic function, as is the density of *Varroa* infestation within a given area of crop. Satellite infestation can also occur randomly in any given year via a logistic process dependent on the total area affected in the previous year (Harris & Harbo 1999). For a full description of these parameters and the complete model see Cook et al. (2007).

Table 5 Biological parameters used in the economic model

Parameter	Assumed Parameter Value[1]
Crop area (Ha) currently affected by *Varroa*	PERT(10,30,50) (Cook et al 2007) [2]
Maximum crop area (Ha) affected	UNIFORM(82000,100000) (Bourke & Harwood 2009)[3]
Population growth rate	PERT(0.20,0.35,0.50)
Current population density	PERT(5.0%,7.5%,10.0%)
Carrying capacity at maximum density of infestation	PERT(70%,85%,100%)
Maximum attainable no. satellite sites	PERT(30,40,50)
Minimum no. satellite sites	PERT(0,5,10)
Intrinsic rate of satellite generation	PERT(1.0×10-3,5.95×10-3,1.0×10-2)

[1] All parameter values are taken from Cook et al. (2007) unless otherwise stated.
[2] The term "PERT" is an acronym for the Program Evaluation and Review Technique, used to form a special case of the beta distribution using lower boundary (minimum), modal (most likely) and upper boundary (maximum) parameters (Vose, D.2000).
[3] The term "UNIFORM" refers to a rectangular distribution specified using a lower boundary (minimum) and an upper boundary (maximum).

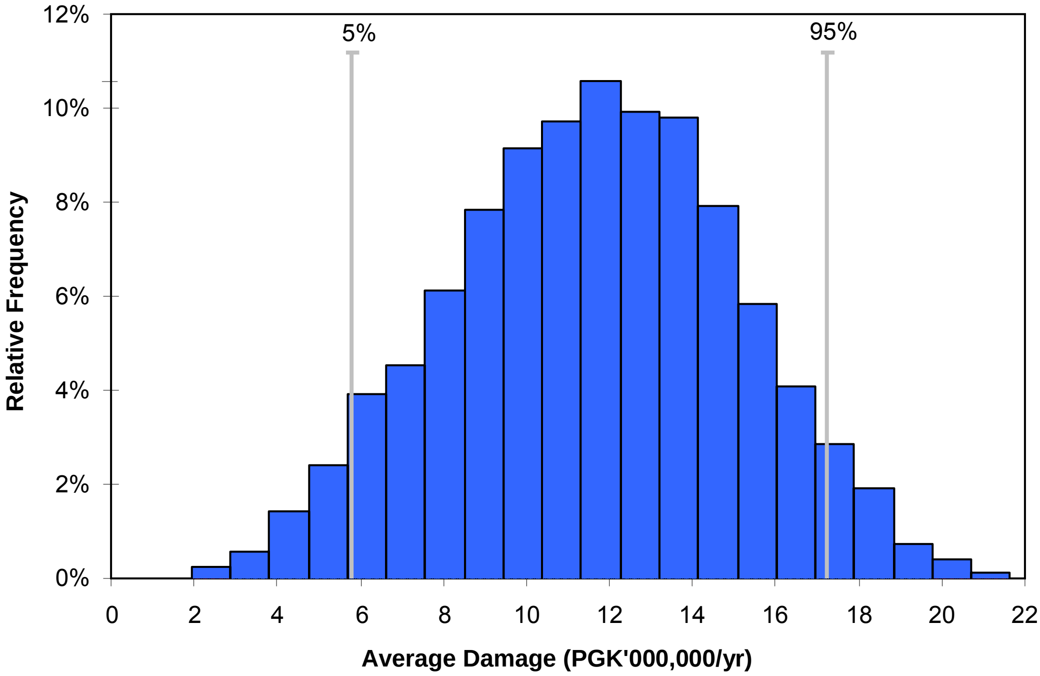
We used 5,000 iterations of the model in which one value is randomly sampled across the range of each distribution. The advantage of using this approach is that it provides an indication of the complete set of damage scenarios weighted by probability. However, since we have assumed the complete independence of parameters, the tails of the expected damage distribution may be over-stated in the results. Nevertheless, for the purposes of this discussion we simply acknowledge this to be the case.

Taking the mean of the distribution of expected damage costs over a 30-year simulation (i.e. PV(EDn)/n), we estimate that the average damage to the PNG coffee industry attributable to *Varroa* will be PGK11.6 million per year over 30 years. This is equivalent to a loss of 3.7% of the annual combined GVP of all highland coffee growing regions. A similar decline in coffee production might be experienced if coffee prices were to fall by PGK0.20/kg from their current levels (i.e. PGK5.00-5.45/kg for Y1 Grade Arabica (Coffee Industry Corporation Ltd. 2008). Although such a drop in prices would be severe, it is worth noting the World Bank predicts prices may fall to as low as PGK4.50/kg by 2015 (Bourke and Harwood 2009), which would be a much larger effect.

Due to the uncertainty and variability of the parameter estimates used in the model our confidence intervals are broad. Results indicate a 90% likelihood of damages between PGK5.8 million (1.8% of GVP) and PGK17.2 million (5.5% of GVP) per annum. Figure 3 presents the relative frequency distribution for average annual damage over the 30-year period following establishment.

Our assumptions imply the spread of *Varroa* through wild bee colonies will occur slowly at first before accelerating rapidly. Figure 4 plots the crop area affected by decreased honey bee pollination over time. This diagram suggests insect pollination services will remain largely unchanged until approximately year 15. This inflexion (or threshold) point in the area curve corresponds to a sudden rise in the *Varroa* population after an initial incubation period during which it gains a foothold in the natural environment.

Figure 3 Average damage to the PNG coffee industry from Varroa incursion over 30 years, estimated by the model



If in fact the new *Varroa* evolved and established a viable population in PNG in 2003 (Anderson 2008) we are currently at year 6 of the population growth curve. According to the model, the current area of coffee plantations experiencing yield declines due to loss of honeybees is between 250ha and 1,350ha with a most likely area of 675ha.

Translating the affected area data into economic losses in Figure 5, we see a similar pattern to Figure 4 with the periods of highest impact expected to occur 10-20 years after the establishment of the initial population. Thereafter, the effects of discounting erode damage estimates. Note also that this figure illustrates the uncertainty surrounding the predictive model. The values expressed in this figure are in current value terms (i.e. PV(EDn) from expression (1)).

Assuming we are currently in year 6 of *Varroa's* population growth, PNG is approaching a time where its impact will increase dramatically. Our model predicts that current coffee yield losses attributable to the mite are between PGK0.2-1.2 million per year, with a most likely loss of PGK0.6 million per year. Up to this point accumulated damages of PGK1.2 million will have occurred in the 6 years *Varroa* has been present up to 2009. We predict that the average annual impact on national coffee production calculated between year 6 (rather than year 0) and year 30 of the invasion is likely to be between PGK5.3-23.9 million. The most likely damage figure calculated from year 6 to 30 is PGK14.2 million per year (i.e. above the average damage calculated from year 0 (PGK11.6 million)).

If the range of scenarios encapsulated in this model are realistic, these predictions indicate that if efforts to reduce the impact of *Varroa* were successful the likely returns to the coffee industry are high enough to warrant a significant investment. For instance, if we were to take a minimum-impact scenario where predicted damages correspond to the 5% confidence interval of Figure 5 an eradication project may be warranted up to a value of PGK5.8 million per annum before the ratio of benefits to costs becomes less than one. If we were to take the maximum-impact scenario from the 95% confidence interval of Figure 5, the breakeven level of investment would be as high as PGK17.2 million per year.

Figure 4 Estimated area affected by the Varroa mite in PNG over time, predicted by the model

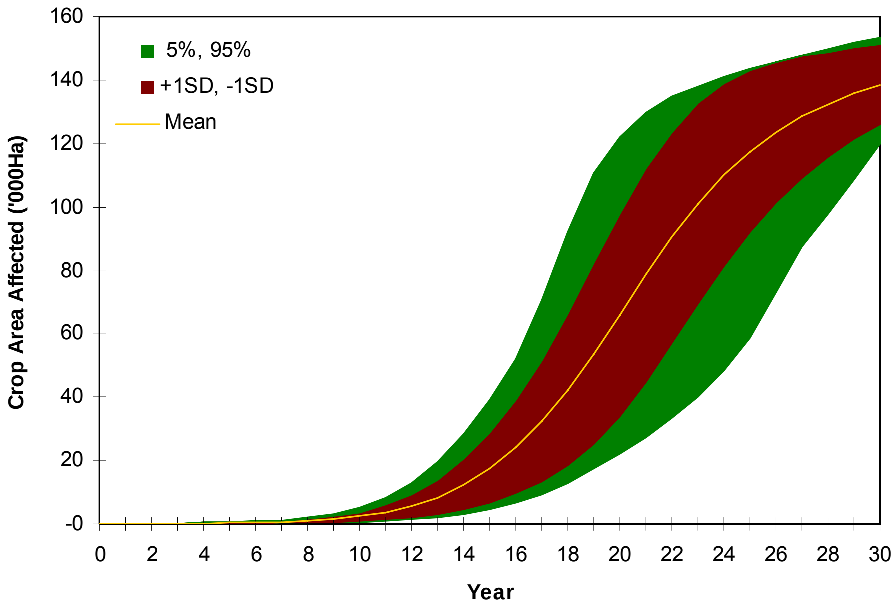
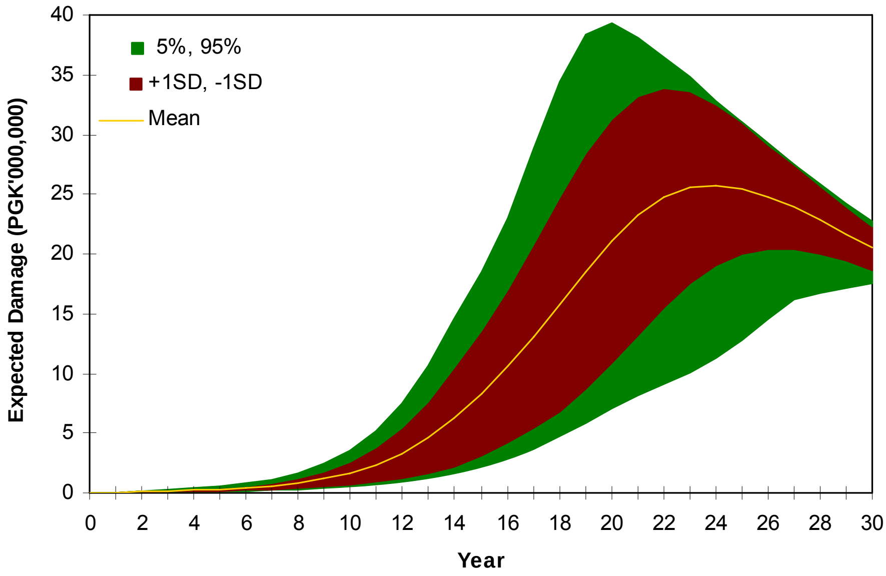


Figure 5 Estimated loss of PNG coffee production over time attributable to the Varroa mite, predicted by the model

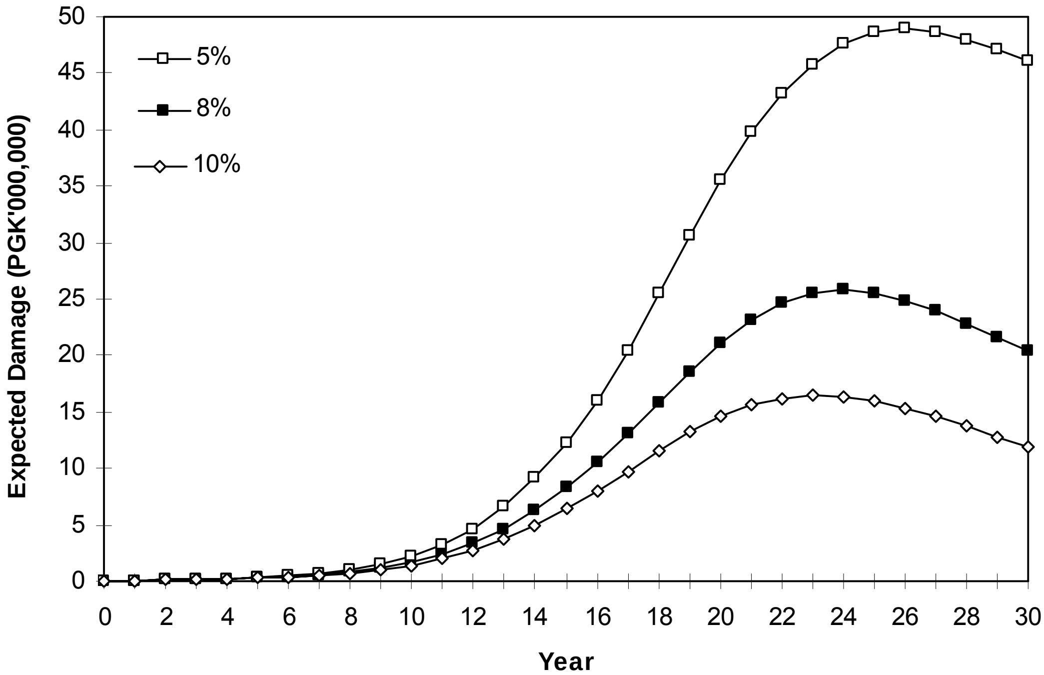


The impact of *Varroa* on individual provinces varies according to the total area devoted to coffee production. As such, the Western Highlands and Eastern Highlands regions are expected to be the most significant beneficiaries of a successful eradication campaign over time. We note that the relative profitability of coffee production is not necessarily proportional to the overall size of the industry within a given province. However, accurate production data are not currently available to ascertain producer profit by growing region. It is therefore difficult to comment on the capacity of coffee growers within each province to withstand the yield losses expected to result from *Varroa*.

Sensitivity analysis with the model indicates the variables with the greatest influence on results are the *Varroa* population growth rate, the yield loss attributable to insect pollination reduction and the discount rate. We therefore suggest that large reductions in expected incursion damage could be achieved by targeting these (or at least the first two) variables. Using a hypothetical example to illustrate this point, let us assume the intrinsic rate of population growth can be lowered by 25% as a result of PGK2.0 million per year being invested in spread mitigation. If this were achieved we predict a benefit/cost ratio of 2.7:1 would result with approximately PGK163.4 million prevented damages over 30 years (or PGK5.4 million per year).

While the choice of discount rate is an important assumption in our analysis it is difficult to choose an appropriate value. In the absence of definitive information on opportunity costs relevant to a specific project like *Varroa* control, we use a standard discount rate of 8% which consists of a margin of 3% on top of a real risk-free rate of 5% (Department of Finance 1991; Commonwealth of Australia 2006). The discount rate perspective makes sense from the point of view of a decision maker that is well informed has a long term outlook, and a range of alternative investments to choose from. It is a less meaningful concept when applied to decisions made by individual producers (in this case, the smallholding coffee grower). Figure 6 demonstrates the effects of both a higher discount rate and a lower discount rate. If, for example we were to apply a personal discount rate of 10% (as opposed to a public/social discount rate) to model calculations the annual benefits of eradication and exclusion over 30 years would fall to PGK7.7 million. Conversely, if we were to adopt a much more precautionary approach to agricultural change and apply a discount rate of 5%, average annual benefits to PGK21.1 million over 30 years.

Figure 6 Sensitivity of model predictions to changes in the discount rate



While sensitivity analysis on individual parameters within the model is interesting, the assumption of independence between them invariably means results will be relatively insensitive to changes in their values. However, by simultaneously altering two or more parameters the effects of one parameter may exacerbate another and lead to a more significant change in the damage predicted over time. Ninety percent of all possible combinations of effects are captured within the shaded regions of Figures 4 & 5, but let us discuss a hypothetical scenario in which: (1) the *Varroa* population growth rate is 0.5/yr and we are already 6 years into the process (2) the impact of *Apis mellifera* decline is a 50% decline in yield, and (3) the maximum area of crop affected is 100,000Ha, and (4) the appropriate discount rate is 5%. The likelihood of such an occurrence is extremely low since it effectively involves events in the extreme right tail of 3 distributions occurring simultaneously. But, should it occur, the average yearly damage to the PNG Arabica coffee industry over 24 years simulated in the model increases to PGK50.3 million. Note that this scenario does not occur in Figure 3 because that model used a discount rate of 8%. This extreme scenario can be thought of as lying in the far right-hand tail of a distribution like that in Figure 3, but shifted toward a higher mean level of impact.

Our analysis presents a scenario in which the PNG pollinator community provides no pollination in the absence of *Apis mellifera*. In effect, it presents a worst-case scenario for coffee producers since it assumes native and other introduced pollinators (e.g. *Apis cerana*) are incapable of filling the void if *Apis mellifera* are removed by *Varroa*. It is therefore important to speculate what the likely impact on our results would be if the pollinator community did display some form of resilience in crop pollination. This would have the effect of lessening the impact of *Varroa* as it spreads through the regions. But, how large or small will the change in overall impact over time be?

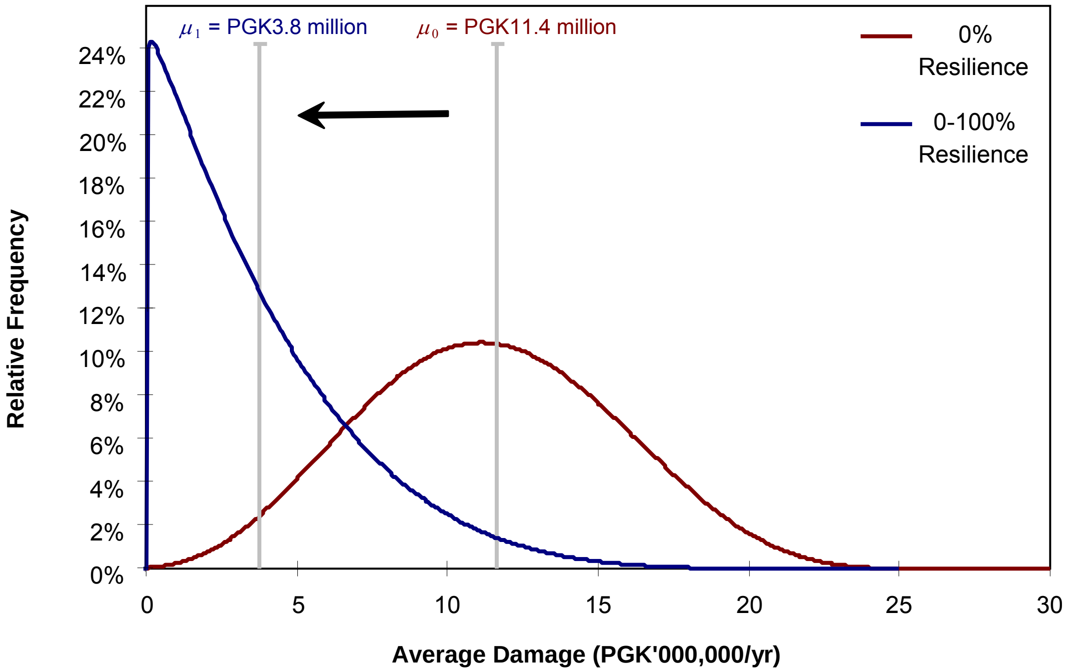
To answer this question, we considered possible outcomes ranging from 0-100% resilience levels of local pollinator communities. Under our worst-case scenario, described above, *Varroa* is likely to cause damages in the order of PGK11.6 million per year over time. However, under a best-case scenario where there is perfect substitution of pollinators the impact of *Varroa* is zero. To simulate the continuum of possibilities between these two extremes we included a simple pollinator community multiplier (β) in the model. The resilience multiplier was specified as a triangular distribution with a minimum value of 0% (full resilience, change in service is zero), a maximum of 100% (no resilience, change in service is a complete loss of pollination) and a most-likely value of 0% (i.e. Triangular (0%, 0%, 100%)). This reflects a hypothesis that a strong capacity to compensate for the loss of *Apis mellifera* is more likely than a complete lack of compensation. This in turn implies β will be distributed with a left-hand bias. The multiplier was applied to yield effects such that:

$$\mathrm{PV}(\mathrm{ED}_n) = \sum_{t=0}^{n} (1+\alpha)^{-t} . \sum_{j=1}^{s_t} p.d.\beta.A.N \qquad (2)$$

This had the effect of shifting the distribution of average damage (shown in Figure 3) to the left. The extent of this shift is shown in Figure 7. Here the distribution of expected damage under both the 0% resilience (i.e. worst case) and the 0-100% resilience (i.e. using the pollinator community multiplier, β) are shown using distributions fitted with the @Risk software package. Both are Beta General distributions specified with minimum and maximum values and two shape parameters. The distribution of average yearly damage from *Varroa* if the pollinator community exhibits no resilience, shown in dark red, has a minimum value of PGK1.1, a maximum value of PGK22.1 million and shape parameters of 3.3 and 532.0 (i.e. BetaGeneral(1.1, 3.3, 532.0, 22160530)). Using the pollinator resilience multiplier model average damage, shown in dark blue, is given by BetaGeneral(1.0, 5.2, 81.9, 22959107). The respective means of these distributions, are shown in Figure 7. The decrease in average damage caused by β is therefore 66.7%.

In the model depicted (Figure 7) the resilience multiplier has been applied to the base model (i.e equivalent to Figure 3). If, however, the resilience multiplier is instead applied to a model assuming that we are already in year 6 of *Varroa* invasion, then resilience effect moves the mean from PGK 14.2 million (μ_0) down to PGK 4.7 million (μ_1).

Figure 7 Distribution of average damage predicted by the model under different pollinator resilience scenarios



5.10 Survey of visitors to flowers of crops in PNG

A survey was conducted (Solomon Balagawi and Graham Mesa) ranging from the Coastal lowlands to the Highlands of PNG, focusing on important target crops. The main objective was to establish whether *Apis mellifera* and *cerana* are important visitors of these target crops. If not, then what other insect species are important visitors to flowers of these target crops? Establishment of such facts should provide better understanding to the fight currently being pursued by the Honey Bee Farmer Association in PNG to manage the new strain of *Varroa jacobsoni*.

5.10.1 Materials and Methods

Before the survey was conducted, a team of experts from NARI, EHPDAL, National DAL, Goroka University, CIC and CSIRO identified the target crops that should be surveyed. These crops were identified due to their importance in food security and cash income generation to PNG. The crops identified are listed in table 6.

Table 6: Crops considered for the flower visitor survey

Cash crops	Staple crops	Vegetables	Fruits
Coconut	Sweet potato	Cole crops	Citrus
Coffee	Taro	Aibika	Mango
Oil palm	Banana	Capsicum	Pineapples
Cocoa	Yam	Tomato	Pawpaw
Betelnut	Sago	Cucurbits	Avocado
Sugarcane	Cassava	Maize/corn	
		peanut	

The survey covered 5 provinces which included both the costal lowland and the highland provinces of PNG. The coastal lowland provinces covered in this survey were the Central, Madang and Morobe provinces while Eastern Highlands (EHP) and Western Highlands provinces (WHP) were surveyed in the Highlands region. The survey began in the Central province on 7 January 2009 and terminated on 19 February 2009 in the WHP.

At each observation site, the flowering target crops were identified and the observer spent 30 minutes observing each crop and tallying the number of visitations made by each insect species to the observed flowers. The visitation was categorized into those visits that resulted in actual contact and foraging on the flower and those that did not make any contact to the flower. Other information collected included number of flowers observed, distance, location and barrier to managed hives, observation time of day and weather at time of observation. Where possible, the insect was collected at the end of the 30 minutes observation period for further identification.

5.10.2 Results & Discussion

The results for the survey are summarized in appendix 4, table 1 for the survey carried out in the two highland provinces while appendix 4 table 2 summarizes the survey data for the coastal lowland provinces. Because of the limited nature of this survey, results should be treated as the basis for development of further research, rather than a comprehensive search.

The European honey been *Apis mellifera* was not seen visiting flowers of any of the crops surveyed in the three lowland provinces surveyed. This could be due to non-availability of managed *Apis mellifera* hives in the vicinity of the crops surveyed. However, in the highlands, *Apis mellifera* were frequent visitors to some crops and managed hives are more often seen. The survey result shows that *Apis mellifera* does visit flowers of corn, pumpkin, banana, sweet potato, coffee, cucumber and bean. Other surveyed crops such as orange, English potato, choko, tomato, broccoli, strawberry, egg plant, avocado and pyrethrum did not receive any visitation from *Apis mellifera*. This could have resulted simply due to lower number of the flowers surveyed rather than that *Apis mellifera* do not visit these crops.

The survey results shows that the Asian honey bee, *Apis cerana*, could play a significant role in crop pollination in both the highlands and the coastal lowland areas in PNG. Even at sites (especially in the highlands) where managed *Apis mellifera* hives are present, *Apis cerana* seems to play more significant role in pollination than A. mellifera. Furthermore, *Apis cerana* is one of the main pollinators to most of the target crops surveyed in both the coastal lowlands and the highlands region (see appendix 4). Other bees that may be specific pollinators to certain crops include *Lassioglosum* sp, *Vespa affinis molucana*, *Anthophora* sp, *Campsomeris* sp, *Megachile frontalis*, *Polister tepidus* and *Nomia pulchriteata* (see appendix 4).

6 Impacts

6.1 Scientific impacts – now and in 5 years

This research adds to the body of knowledge on the pollination of tropical crops. Findings will be disseminated though publications, including a technical monograph proposed to be published by ACIAR.

6.2 Capacity impacts – now and in 5 years

This project provided significant training for one junior scientist in PNG at NARI (Graham Mesa) and strengthened the capacity of CSIRO to undertake similar research in Australia and in partner countries which ACIAR supports.

6.3 Community impacts – now and in 5 years

The aim of this project was to assess the potential impact of *Varroa* on pollination and therefore the direct impact of the project is a decrease in the uncertainty for the producers of crops, especially coffee, in PNG. The nature of the risk to Australia is better understood. Allocation of resources to the problems generated by *Varroa* for the honey production and cropping industries can now be allocated more efficiently. Better knowledge of other sources of uncertainty (such as fluctuating prices and other crop diseases) is needed before the benefits of this project can be quantified.

6.4 Communication and dissemination activities

Central to the execution of this project were two workshops in PNG (see Appendices 1& 2). These workshops were aimed at knowledge exchange both in the early stage of the project, and then in the reporting phase. After the second workshop we prepared a media release (appendix 3) which was covered by a PNG national newspaper. In addition to these workshops Saul Cunningham presented a seminar at the ACIAR headquarters in Canberra (May 6) to an audience including people from ACIAR and DAFF. Saul Cunningham will also be presenting a seminar at an international Ecology conference in Brisbane in August 2009 (Intecol) focussing on the findings of this study. Cunningham and Cook are also preparing a paper for a refereed international science journal based largely on this work.

7 Conclusions and recommendations

7.1 Conclusions: Summarizing the range of possible impacts

We suggest it is most likely that the new *Varroa* will continue to spread throughout the highlands of PNG where it will dramatically reduce the population of feral *Apis mellifera*. It is most likely that the level of crop pollination will remain high because feral *Apis cerana* will still be present along with a diverse community of native bee species. If, however, the is a decline in crop pollination because of a failure of the community of pollinators to fully compensate for loss of feral *Apis mellifera* the economic impact of this will be felt mostly in reduced yields of the important cash crop, Arabica coffee. Other crops that are vulnerable to pollinator decline in the highlands are relatively much smaller in economic importance and adapting to any changes is likely to be easier.

In the worst case scenario the average yearly damage to the PNG Arabica coffee industry over 24 years could be PGK50.3 million. However, this model assumes that all of the most pessimistic conditions are met. We suggest that real impacts will be much lower, especially because *Apis cerana* and native bees are expected to at the very least partially compensate for loss of *Apis mellifera*.

There is a small possibility that the new *Varroa* could move on to *Apis cerana* and cause greater pathogenicity than the form of *Varroa jacobsoni* that already afflicts *Apis cerana*. If this were to happen pollinator decline would be more substantial in the highlands (because of loss of a second feral *Apis* species), and would also spread to the lowlands (where *cerana* is the only *Apis* species). In the highlands this would be equivalent to reducing the degree to which the remaining community of pollinators can compensate for loss of *Varroa*, and in that sense is a special case of the economic model presented. The move to the lowlands, however, creates additional potential crop impacts. However, we expect this additional effect would be substantially smaller than that experienced in the highlands. Each of the four major cash crops in the lowlands has circumstances that mitigate against strong economic impact of potential *Apis* decline:

- Cocoa is not pollinated by bees
- Coconut is of shrinking economic importance and is less dependent on insect pollination than coffee
- Oil palm, although of growing economic significance, is known to be best pollinated by weevils which can be introduced into plantations
- Betelnut palm is poorly studied, but what evidence there is suggests little or no reliance on pollinators. Further, it is not usually grown in large plantations.

Although the greatest impacts are predicted to be felt through the loss of feral *Apis* it should be recognised that declines in managed *Apis mellifera* are highly likely in any scenario. We suggest that this will have little effect on current agricultural practice, because the provision of managed pollination services is relatively uncommon in PNG. It is important, however, to recognise that a decline in *Apis mellifera* beekeeping would represent a lost opportunity for improved crop pollination. For example, improving coffee quality has been seen as a prospect for improved agricultural returns (Batt et al. 2009), but loss of beekeepers would make it more difficult to ensure the production of large size premium coffee beans.

7.2 Recommendations

Our economic analysis provides a basis for deciding how much money could be spent on activities that will help reduce economic impact of the new *Varroa* mite. Here we suggest research questions that either improve our certainty around the likelihood of different scenarios, or suggest possible paths to impact reduction. We are aware that in some cases research is already underway that will help answer these questions.

7.2.1 Bee questions

Q: Are feral *Apis mellifera* frequent flower visitors of important crops, including coffee?

Implications: The answer to this question would help us understand the potential impact of loss of feral *Apis mellifera*. It would need to be assessed in areas that are not yet affected by *Varroa* (if this can be established).

Q: Are *Apis cerana* competing with *Apis mellifera* for access to important pollinator limited crops or for nesting sites?

Implications: If the two *Apis* species are currently competing then loss of *Apis mellifera* is likely to be strongly compensated for by increased *Apis cerana*.

Q: Can *Apis cerana* be domesticated to the point that it would be useful for managed pollination services?

Implications: If *Apis cerana* can be selected to reduce its tendency to swarm and abscond then it could fill the managed pollination void left by *Apis mellifera*.

7.2.2 Coffee questions

Q: What varieties of Arabica coffee are being grown in PNG and how is fruit set affected by excluding pollinators?

Implications: The answer to these questions would help us narrow the uncertainty around the size of the pollinator effect on fruit set – which we modelled assuming a range between 25-52%.

Q: How effective is *Apis cerana* as a pollinator of Arabica coffee? How effective are native bees as pollinators of Arabica coffee in highland PNG?

Implications: The answer to these questions would help us to understand the likely resilience of the crop pollination response of the unmanaged bee community. This variable can cause impacts to range from the maximum modelled, all the way down to zero impact if unmanaged bees are effective pollinators.

Q: Is there potential for PNG coffee producers to increase the fraction of the crop sold at a premium? To what extent is bean size a limiting factor in attaining this premium?

Implications: The answer to these questions would help us to understand the opportunity cost associated with a decline in beekeeping. If there is strong potential to increase the amount of premium grade coffee this would increase the future benefits associated with managed crop pollination. Research by Batt et al. (2009) identifies other barriers to attaining a premium, but did not consider opportunities for increasing quality through pollination management.

7.2.3 *Varroa* questions

Although *Varroa* biology was not in scope for this project, we can conclude that certain questions about *Varroa* have a great impact on potential crop production effects.

Q: How probable is a host shift event in which the new *Varroa* shifts back on to *Apis cerana* and then displays increased pathogenicity?

Implications: If this were to happen, the probability of pollination impacts in the highlands increases, and there would be a spread of the risk to the lowlands through declining *Apis cerana*.

Q: What impact has the new *Varroa* (or associated vectored pathogens) had on the feral *Apis mellifera* populations in areas that it already infests?

Implications: If the impact of the new *Varroa* is already well advanced and widespread this would make control even more difficult, and would bring forward the period in which pollination declines could be experienced. By reducing the size of the discounting effect this increases the economic impact.

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9 Appendices

9.1 Appendix 1: Participants in the 27-28 November workshop in Aiyura, PNG

PDAL (Provincial Office Department of Agriculture and Livestock)

- Jonah Buka: Full time beekeeper and beekeeping extension officer
- Tella Loie: Apiculture technician from Eastern Highlands province office: local knowledge of beekeeping and cropping in the highland provinces. Long history in beekeeping extension
- Leon Saleu: Apiculture expert
- Igu Yawane: In charge of Livestock section, western highlands provincial office – has experience with beekeeping

CIC (Coffee Industry Corporation)

- Ingu Bofeng

NARI (National Agricultural Research Institute)

- Akkinapally Ramakrishna: Agronomist and research program leader
- Workneh Ayalew: Leader of Livestock Research ; Animal scientist with overall supervision of the PNG components of the ACIAR funded research
- Solomon Balagawi: Entomologist with an active role in planning of project activities; identifying information sources; reviewing literature; linking to relevant activities in collaborating institutions in PNG;
- Mark Ero: Entomologist – Phd from UQ
- Graham Mesa: Graduate biologist (masters) responsible for collecting data on bee visitors to PNG crops
- Dr John Bailey: Research program leader at Aiyura; facilitation of project activities in the highlands region
- Rakesh Kapila: Principal crop breeder
- Robert Plak: Crop improvement and breeding
- Triya Papaya: Research technician based at Aiyura; local knowledge of cropping and beekeeping in the area.
- Cheryl Ivahupa: Research officer, has worked with ANU RSPAS research project surveying PNG agriculture
  CSIRO Entomology
- Dr Saul Cunningham
- Dr Paul De Barro

9.2 Appendix 2: Report of 14 May workshop in Lae, PNG, and list of participants

Report by Doug Gray

ACIAR does not have definite plans to make further investments in this area but was able to make a strong offer that we would publish a technical report on the outputs of the scoping study and the related studies by NAQIA/AQIS. Suggested chapters for that publication are:

Title: Implications of the of the Varroa bee mite incursion on food and cash crop production1 in Papua New Guinea.

[1] *includes honey*

1. Overview of problem, findings and recommendations
2. Defining crops of interest
3. Economic impact on coffee
4. Discovery of Destructive Varroa
5. Distribution of Varroa
6. Research questions and their implications

The main findings of the workshop were:

- The new Varroa is widely distributed in PNG, including presence in Bougainville and may have been in PNG for more than 10 years (NAQIA survey).
- The major potential loss of pollinations services is to the coffee crop (CSIRO and NARI)
- The upper limit of potential losses to the coffee crop are very much less that previously feared (in the order of a few percent, not 50% as announced in the press)
- The pathogenicity of the new *Varroa* in managed hives is uncertain: anecdotes suggest that other hive problems are as serious (DAL and NAQIA)
- *Apis mellifera*, *Apis cerana* and other insects known to pollinated coffee have been observed visiting coffee bushes at several sites (NARI).

A communiqué was developed by the group and is attached (appendix 3).

There are three possible pathways forward for research investment:

- General development of an organic honey industry in which *Varroa* is just one of many constraints. The current number of managed hives is only about 5% that needed to pollinate the existing coffee crop. Prices for local honey are high to the smallholder: about K10 (A$6) about 4 times the global price for commercial honey.
- Comprehensive project on the opportunities (and constraints) to improve pollination services to coffee, cucumber, water melon and as yet unknown indigenous fruits and nuts.
- A biosecurity focussed project driven by Australian interests to understand the nature of the threat to Australia (pathogenicity, host specificity, behavioural genetics) and an understanding of the genetics of destructive behaviour leading to upstream research on new control methods for *Varroa* with global significance.

List of Workshop Participants

PDAL (Provincial Office Department of Agriculture and Livestock)

- Bubia Muhuju, Eastern highlands

CIC (Coffee Industry Corporation)

- Nelsen Simbiken

NARI (National Agricultural Research Institute)

- Sergie Bang, Director of Research
- Birte Nass-Komolong, Plant Pathologist
- Keshav Kshirsagar, Principal Economist and Acting Director General
- Workneh Ayalew: Leader of Livestock Research
- Solomon Balagawi, Entomologist
- Mark Ero, Entomologist
- Graham Mesa, Graduate biologist (masters)
- Rakesh Kapila, Principal crop breeder

CSIRO Entomology

- Saul Cunningham

ACIAR

- Doug Gray

NAQIA

- Nime Kapo
- Martin Pascalus
- Raphael Kababa

9.3 Appendix 3: Media Release after Lae Workshop

Potential economic impact of new Varroa mite on PNG coffee

Saul A. Cunningham, David C. Cook, Paul J. De Barro, Workneh Ayalew, Solomon Balagawi

CSIRO Entomology, Australia and NARI, Papua New Guinea

A research collaboration between Australian and PNG scientists revealed that the potential economic impact of the *Varroa* mite on agriculture in PNG is likely to be much less than earlier speculated. This was made public in a research review workshop hosted by NARI in Lae on 14 May 2009. Participating at this workshop were representatives from NARI, CSIRO, ACIAR, NAQIA, CIC and provincial DAL from Eastern Highlands.

The new bee mite was discovered in the Eastern Highlands of PNG in May 2008. This discovery attracted the attention of many stakeholders. It was feared that, in addition to threatening managed beekeeping in the highlands, the effect of reduced pollination from European honeybees could cause significant economic losses in the agriculture sector in general. The impact of reduced pollination on coffee production alone was estimated to be as high as a 50% drop in yield, which would mean a loss of about K200 million per annum in the form of reduced coffee export earnings.

In response to this intriguing situation, ACIAR, NARI and CSIRO initiated a scoping study to investigate the potential economic impact of reduced pollination by European honeybees on PNG agriculture.

The study surveyed food and cash crops that depend on insect pollination as well as assessing their degree of dependence on insect pollination. It also surveyed pollinator insects that visit selected dependent crops both in the highlands and lowlands of the country. In PNG, the distribution of managed European honeybees (*Apis mellifera*) is restricted to the cooler highlands of PNG, whereas the feral *Apis cerana* are found throughout the country. The relative importance of the two *Apis* species in crop pollination in PNG remains to be investigated. However, based on established knowledge elsewhere, it is expected that *Apis mellifera* provide significant pollination services to dependent crops in the highlands for critical crops like coffee, cucumber and orchard tree crops. Pollinator dependent lowland crops like coconuts, oil palm and some vegetables get these services from *Apis cerana* and other pollinator insects that do not appear to have been affected by the new strain of *Varroa* mite. In view of its relatively high contribution to annual cash incomes of smallholder farmers in the densely populated highlands of PNG, and hence its significance to the national economy, the scoping study focused on the likely economic impact that mite may have on the PNG highland (Arabica) coffee.

The study developed an economic simulation model to estimate probable economic losses from coffee production over a period of years. The key assumptions of this model were that: 1) the new *Varroa* mite population will grow and spread over time; 2) due to uncertainties in estimates of damage to coffee yield, a range of possible outcomes are possible; 3) the mite was considered to have originated about six years ago, and 4) the maximum effects will not be instantaneous as invasion by the mite and its population growth take time. The study found that the worst case scenario, in which no insects except *Apis mellifera* provide pollination service to coffee, would lead to K14 million loss from coffee production annually over the next 24 years (i.e. the earlier estimate of K200 million loss was too high). It is likely, however, that other insects such as *Apis cerana* and native bees will continue to pollinate coffee, in which case the impact will be even smaller than K14 million. The workshop concluded that targeted research could give us much more confidence in estimating whether the impacts are closer to K14 million or K4 million annually. Research is needed on coffee pollination in PNG style coffee gardens: which insects are involved, and how much do they boost yield? This same research will not only help understand risks posed by *Varroa*, but will help us improve coffee production practices into the future.

Preliminary findings from a separate survey of *Varroa* mites in all provinces of PNG indicated that the mite is indeed widespread in the country, suggesting the need to initiate appropriate and sustainable parasite management interventions. The coffee industry is already experiencing a gradual decline in supplies of coffee to the market, but the causes for this decline are yet unknown. Further research work is needed to identify the possible causes and assess their relative importance.

This study was jointly undertaken by three scientists from the CSIRO and two scientists from NARI, with direct funding from ACIAR and RIRDC as well as in kind contributions from CSIRO and NARI.

Further information about results of this study can be obtained from Dr. Saul Cunningham of CSIRO in Canberra (Email: Saul.Cunningham@csiro.au) or Dr. Workneh Ayalew of NARI in Lae (Email: workneh.ayalew@nari.org.pg).

The final report from the scoping study will be available from ACIAR later in 2009.

9.4 Appendix 4: Survey of flower visiting insects

Table 1: Results of flower visitor survey in highland provinces.

Crop	No. of flowers	Province & location	Weather	Dist. From managed hives	Barrier from managed hives	*Apis mellifera* No. of visits to flowers	*Apis mellifera* No. of visit to plant but not flowers	*Apis cerena* No. of visits to flowers	*Apis cerena* No. of visit to plant but not flowers	Other Bees No. of visits to flowers	Other Bees No. of visit to plant but not flowers	Other insects Name of insect & (no. visit to flowers)	Other insects Name of insect & (no. visit to plant but not flowers)
Corn	5	EHP (Aiyura)	sunny	300m (hillside)	buildings	0	0	2	0	0	0	*Oribius* sp (1)	0
	1	EHP (Onamuna)	sunny	4000m (hillside)	mountain & forest	0	0	4	0	0	0	0	0
	3	EHP (Dotiwara)	cloudy	200m (hillside)	nil	7	0	7	0	0	0	0	0
	2	WHP (HATC)	Wet & cloudy	1000m (flatland)	crop plantation	0	0	0	0	0	0	0	0
	2	WHP (Tambul)	Wet & cloudy	no hive	-	0	0	0	0	0	0	0	0
Pumpkin	3	EHP (Aiyura)	sunny & cold	100m (flatland)	buildings	2	0	4	0	0	0	0	0
	3	EHP (Onamuna)	sunny	4000m (hillside)	mountain & forest	0	0	10	0	0	0	0	0
	2	EHP (Dotiwara)	cloudy	200m (hillside)	nil	3	0	4	0	0	0	0	0
	3	WHP (Minj)	wet & cloudy	5000m (flatland)	Crop plantation	0	0	1	0	0	0	*Lema unicentus* (3)	0
	2	WHP (Tambul)	Wet & cloudy	no hive	-	8	0	10	0	0	0	0	0
Banana	2	EHP (Aiyura)	hot & sunny	150m (hillside)	nil	0	0	10	0	*Polister tepidus* (1)	0	0	0
	2	EHP (Onamuna)	sunny	4000m (hillside)	mountain & forest	0	0	11	0	0	0	0	0
	1	EHP (Dotiwara)	cloudy	350 m (hillside)	Crop plantation	9	0	17	0	0	0	0	0
	1	WHP (HATC)	wet & cloudy	1000m (flatland)	crop plantation	0	0	0	0	0	0	0	0
	1	WHP (Minj)	Wet & cloudy	5000m (flatland)	crop plantation	0	0	7	0	0	0	0	0
Sweet potato	6	EHP (Aiyura)	cloudy	400m (flatland)	crop plantation	8	0	10	0	0	0	0	0
	4	EHP (Onamuna)	sunny	4500m (hillside)	mountain & forest	2	0	0	0	*Nomia pulchribalteata* ? (3)	0	0	0
	5	EHP (Dotiwara)	cloudy	350m (hillside)	crop plantation	0	0	2	0	0	0	0	0
	12	WHP (HATC)	wet & cloudy	1000m (flatland)	crop plantation	0	0	3	0	0	0	*Aulachophora* sp beetle (1), *Oribius inimicus* (1)	0
	10	WHP (Tambul)	wet & cloudy	no hive	-	0	0	10	0	0	0	Blue fly (2), fly (2), wasp (2)	0
Coffee	10	EHP (Aiyura)	cloudy	250m (flatland)	nil	6	0	4	0	0	0	0	0
	6	EHP (Onamuna)	sunny	5000m (hillside)	mountain & forest	0	0	4	0	*Nomia pulchribalteata* ? (3)	0	0	0
	5	EHP (Dotiwara)	cloudy	200m (hillside)	crop plantation	1	0	3	0	0	0	0	0
	2	WHP (HATC)	wet & cloudy	1000m Flatland)	crop plantation	0	0	0	0	0	0	0	0
	15	WHP (Minj)	wet & cloudy	5000m (flatland)	crop plantation	0	0	1	0	0	0	0	0
Capsicum	4	EHP (Aiyura)	sunny	200m (hillside)	buildings	0	0	4	0	0	0	0	0
	3	EHP (Onamuna)	sunny	3500m (hillside)	mountain & forest	0	0	1	0	*Nomia* sp (1)	0	0	0
	2	EHP (Dotiwara)	cloudy	320m (hillside)	crop plantation	0	0	3	0	0	0	0	0
	4	WHP (HATC)	wet & cloudy	1000m (flatland)	crop plantation	0		0	0	0	0	0	0
English potato	4	EHP (Aiyura)	cloudy	150m (hillside)	nil	0	0	0	0	*Nomia pulchribalteata* ? (5)	0	0	0
	multiple	WHP (Tambul)	wet & cloudy	no hive	-	0	0	0	0	0	0	0	0
Orange	3	EHP (Aiyura)	sunny	2m (flatland)	nil	0	0	0	0	0	0	0	0
	7	WHP (Minj)	wet & cloudy	5000m (flatland)	crop plantation	0	0	0	0	0	0	*Oribius destructor* (1), Blue fly (4), Flea beetle (1), *Aulachophora* sp beetle (1)	0
Cucumber	4	EHP (Dotiwara)	cloudy	300m (hillside)	crop plantation	10	0	0	0	0	0	0	0
Choko	2	EHP (Aiyura)	cloudy	100m (flatland)	buildings	0	0	4	0	0	0	0	0
	4	WHP (Minj)	wet & cloudy	5000m (flatland)	crop plantation	0	0	0	0	0	0	0	0
Tomato	6	EHP (Aiyura)	sunny	450m (hillside)	buildings	0	0	1	0	0	0	0	0
Broccoli	multiple	EHP (Aiyura)	sunny	450m (hillside)	buildings	0	0	7	0	*Nomia pulchribalteata* ? (3)	0	Unidentified sp (3)	0
Strawberry	4	EHP (Onamuna)	sunny	3500m (hillside)	mountain & forest	0	0	7	0	0	0	0	0
Egg plant	7	WHP (HATC)	wet & cloudy	1000m (flatland)	crop plantation	0	0	0	0	0	0	*Henosepilachna* sp? (1), *Eurinome* sp? (1), Fly (1)	0
Bean	15	WHP (HATC)	wet & cloudy	1000m (flatland)	crop plantation	0	0	0	0	0	0	Fly (1)	0
	15	WHP (Tambul)	wet & cloudy	no hive		5	0	11	0	0	0	0	0
Avocado	multiple	EHP (Onamuna)	sunny	4000m (hillside)	mountain & forest	0	0	3	0	0	0	0	0
Pyrethrum	6	WHP (Tambul)	wet & cloudy	no hive	-	0	0	>10				*Scaptia* sp fly (3)	0

Table 2: Results of flower visitor survey in lowland provinces. No Apis mellifera hives were observed in any of these locations.

Crop	No. of flowers	Province & location	Weather	*Apis mellifera* No. of visits to flowers	*Apis mellifera* No. of visit to plant but not flowers	*Apis cerena* No. of visits to flowers	*Apis cerena* No. of visit to plant but not flowers	Other Bees No. of visits to flowers	Other Bees No. of visit to plant but not flowers	Other insects Name of insect & (no. visit to flowers)	Other insects Name of insect & (no. visit to plant but not flowers)
Corn	8	Central (Laloki)	wet & cloudy	0	0	10	0	0	0	*Ischiopsopha ignipennis* (1)	*Lucilia porphyrina* (1)
	2	Madang (Omoru)	hot & sunny	0	0	3	0	0	0	*Aulacophora sp* beetle (5)	0
	3	Morobe (Bubia)	sunny & windy	0	0	10	0	0	0	0	0
	2	Morobe (Erab)	cloudy & windy	0	0	5	0	0	0	0	0
	2	Morobe (Mutzing)	wet & cold	0	0	3	0	0	0	0	0
Pumpkin	3	Central (Laloki)	wet & cloudy	0	0	0	0	0	0	*Lema unicentus* (>10)	0
	2	Madang (Omoru)	hot & sunny	0	0	0	0	0	0	0	0
	1	Madang (Walium)	wet	0	0	0	0	1	0	ants (3)	0
	1	Morobe (Bubia)	sunny & windy	0	0	2	0	0	0	0	0
	3	Morobe (Erab)	hot & cloudy	0	0	0	0	Unidentified (2) *Lassioglossum* sp	0	0	0
	3	Morobe (Mutzing)	wet & cold	0	0	6	0	0	0	0	0
Banana	3	Central (Laloki)	wet & cloudy	0	0	3	0	*Vespa affinis moluccana* (3)	0	0	0
	1	Madang (Walium)	wet	0	0	7	0	0	0	0	0
	1	Morobe (Bubia)	sunny	0	0	2	0	0	0	0	0
	1	Morobe (Nasuapam)	hot & sunny	0	0	0	0	0	0	0	0
	1	Morobe (Erab)	cloudy & windy	0	0	4	0	0	0	0	0
	1	Morobe (Mutzing)	sunny	0	0	6	0	0	0	Blue fly (1)	0
Sweet potato	6	Central (Laloki)	hot & cloudy	0	0	7	0	0	0	0	0
	2	Morobe (Bubia)	sunny & windy	0	0	1	0	0	0	0	0
Papaya	6	Central (Viemauri)	hot & sunny	0	0	0	0	0	0	0	0
	3	Morobe (Bubia)	sunny & windy	0	0	0	0	0	0	0	0
	2	Morobe (Nasuapam)	hot & sunny	0	0	0	0	0	0	0	0
	5	Morobe (Erab)	cloudy & windy	0	0	0	0	0	0	0	0
	2	Morobe (Mutzing)	wet & cloudy	0	0	0	0	0	0	0	0
Coconut	1	Madang (Murunas)	hot & sunny	0	0	5	0	0	0	Unidentified sp (>10)	0
	1	Madang (St Benedicts)	hot & sunny	0	0	5	0	Unidentified (2)	0	0	0
	1	Morobe (Mutzing)	wet & cloudy	0	0	8	0	Unidentified (3)	0	0	0
	1	Morobe (Bubia)	hot & sunny	0	0	10	0	0	0	0	0
Cocoa	9	Madang (Murunas)	hot & sunny	0	0	0	0	0	0	0	0
	6	Madang (Omoru)	hot & sunny	0	0	0	0	0	0	Black ants (>10)	0
	3	Morobe (Mutzing)	sunny	0	0	0	0	0	0	Black ants (>10)	0
Tomato	10	Madang (Omoru)	hot & sunny	0	0	0	0	0	0	0	0
	4	Morobe (Erab)	cloudy & windy	0	0	0	0	Unidentified sp (1)	0	0	0
	4	Morobe (Mutzing)	wet & cloudy	0	0	0	0	*Antophora* sp (4) *Campsomeris* sp (>10)	0	0	0
Capsicum	2	Morobe (Nasuapam)	hot & sunny	0	0	0	0	0	0	0	0
	5	Morobe (Mutzing)	wet & cloudy	0	0	2	0	*Megachile frontalis* (3), *Anthophora* sp (2), *Campsomeris* sp (3)	0	0	0
Taro	1	Madang (Omoru)	hot & sunny	0	0	0	0	0	0	*Bactrocera cucurbitae* (2)	0
Oil Palm	1	Madang (Ramu)	hot & sunny	0	0	0	0	0	0	Ants (3)	0
Cucumber	6	Morobe (Bubia)	sunny & windy	0	0	1	0	Unidentified sp (2)	0	0	0
Rice	multiple	Morobe (Bubia)	sunny	0	0	3	0	0	0	*Leptocharisa solomonsis* (>10), Bug species (5)	0