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Understanding the Spread of Honeybee Pests and Diseases

— An agent-based modelling approach —

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Development Corporation

Understanding the Spread of Honeybee Pests and Diseases

An agent-based modelling approach

by Jonathan Arundel

October 2011

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Foreword

In many countries the practice of migratory beekeeping creates significant biosecurity challenges. Movement dramatically increases the geographical extent of a disease or incursion. Furthermore, as the movement is not random but instead correlated to particular flowering events, this increases the likelihood of contact between infected and uninfected hives. Interactions between migratory colonies and comparatively stationary managed or wild colonies also influence the pattern of spread.

In responding to an incident, biosecurity strategies typically seek to restrict all movement within a nominal zone of infection. The effectiveness of such a strategy is highly dependent on other factors including adequate sampling and surveillance programs. A movement lockdown may also be costly to implement and have significant economic impacts.

The aim of this doctoral research was to identify alternative general control strategies designed specifically for a mixed migratory and stationary population of honeybee colonies. These strategies were to be tested against conventional strategies using computer simulation models that incorporate the physical and environmental characteristics of different areas. The target application of the model were controls for the spread of *Varroa destructor* in Australia.

Although there were too many variables and too many unknowns to make reasonable inferences, suggestions are made to address the limitations uncovered by this doctoral research project.

A RIRDC scholarship was used to prepare this report with funds provided by the Australian Government.

This report is an addition to RIRDC's diverse range of over 2000 research publications and it forms part of our Honeybee R&D program, which aims to improve the productivity and profitability of the Australian bee keeping industry through the organisation, funding and management of a research, development and extension program that is both stakeholder and market-focussed.

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Craig Burns
Managing Director
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Executive Summary

What the report is about

This report outlines the work undertaken by Jonathan Arundel in his PhD candidature at The University of Melbourne. His research focused primarily on an attempt to develop an agent-based model of both managed and wild honeybee colonies and their movements. The purpose of this model was to understand both the spread of honeybee diseases and pests, and the effectiveness of strategies to minimise this spread.

Who is the report targeted at?

Scientists, policy makers and government agencies responsible for managing biosecurity.

Where are the relevant industries located in Australia?

At the time of the last honeybee industry survey in 2006-07, there were 10,000 beekeepers operating 572,000 hives (Crooks and Rural Industries Research and Development Corporation (Australia), 2008). Over 90% of these are managed by just 1,700 part-time and commercial beekeepers. This trend continues, with more than half of the hives in many states operated by less than 5% of the registered beekeepers (Benecke, 2007).

Along geographic lines, New South Wales has the largest number of hives at 236,000; more than the total of the next two largest states Queensland (127,000) and Victoria (99,000) combined (Crooks and Rural Industries Research and Development Corporation (Australia), 2008).

Aims/objectives

The aim was to develop an agent-based model for honeybee disease epidemiology. The benefits of such a model would include both the beekeeping industry, and other industries such as horticulture which rely on honeybees for pollination services.

Methods used

The methods used included the development of a number of different agent-based models to examine different aspects of the overall system of managed hive movements and wild (also known as feral) colonies. The examination of wild colony distributions was supported by extensive field work.

Results/key findings

The original intention of developing a spatio-temporal model to test potential control strategies has not been met. In the case of honeybee disease and pest spread, there are too many variables and too many unknowns to make reasonable inferences. A reasonable attempt to address the limitations of current knowledge could be made through further research.

Implications for relevant stakeholders

Australia faces additional challenges with a Varroa incursion, beyond those encountered in New Zealand. Current biosecurity control strategies, particularly AUSVETPLAN (Animal Health Australia 2008) have been reviewed in recent workshops held with key stakeholders (Turner, 2010). Further work to examine the impact of varying strategies or parameters from those outlined in AUSVETPLAN, as well as the efficacy of hypothetical technology-based improvements in hive movement tracing, beelining and wild colony eradication would provide additional valuable

information to the honeybee industry that could be used in longer term planning for incursion responses.

Recommendations

A recommendation of the research undertaken in this project is that RIRDC consider a trial of a hive tracking scheme across two seasons with a small group of large-scale commercial beekeepers.

Introduction

The Australian honeybee industry

Introduction of honeybees to Australia

The European honeybee, *Apis mellifera*, was first introduced to Australia from England in April 1822 (Barrett, 1995). Early settlers had found previously that the crops they had brought with them from England were not being satisfactorily pollinated and sought to remedy this by importing bees from their homelands. The strain of bees imported was *Apis mellifera mellifera*, and within the first spring these colonies are recorded to have swarmed and started to establish themselves in the Australian bush as a wild population.

Managed colonies

At the time of the last honeybee industry survey in 2006-07, there were 10,000 beekeepers operating 572,000 hives (Crooks and Rural Industries Research and Development Corporation (Australia), 2008). Over 90% of these are managed by just 1,700 part-time and commercial beekeepers. This trend continues, with more than half of the hives in many states operated by less than 5% of the registered beekeepers (Benecke, 2007).

Along geographic lines, New South Wales has the largest number of hives at 236,000; more than the total of the next two largest states Queensland (127,000) and Victoria (99,000) combined (Crooks and Rural Industries Research and Development Corporation (Australia), 2008).

However, dividing beekeeper registrations on the eastern seaboard along state lines fails to acknowledge a defining characteristic of the honeybee industry in Australia; the phenomenon of the migratory or nomadic beekeeper. Beekeepers will commonly move their hives around five to six times per year, and each move can be up to 1000km in distance. Often these moves will have the beekeeper crossing a state boundary in pursuit of a nectar flow or pollination event.

Regulations differ between each state and territory as to what information regarding hive movements and locations needs to be recorded by beekeepers and/or provided to government. In general, it is only government-leased apiary sites whose locations are known, and no further information is readily available on the history of usage of these sites.

Beekeepers locate their hives on private land, with the permission of the farmer or landowner and on public land, by leasing a site from the state government for an annual fee. For each load of bees (roughly between 100 and 300 hives), each commercial beekeeper must keep permanently booked between 8 and 12 sites spread over a large geographic area (Benecke, 2007).

The economic focus of the Australian honeybee industry at the moment is on honey production, the bulk of which is produced from eucalypts. This is in contrast with other countries, not just because of the strong focus on plants of a single genus, but more so because of the lack of an established paid-pollination industry. One reason provided for the current structure is that much pollination occurs incidentally, or free-of-charge, by wild colonies.

Wild colonies

Wild honeybees require the following for survival, all of which they are able to find for themselves in both urban and rural areas:

- Food, in the form of nectar and pollen
- Water
- Shelter, generally in the form of tree hollows in old eucalypt trees

Wild honeybees colonies are present throughout Australia, and populations have been shown to be self-sustaining (Oldroyd et al., 1997) without requiring new swarms from managed colonies. Wild colonies have been identified as providing essential pollination for many crops (Gordon and Davis, 2003). Wild bees are also thought to be important for the spread of disease and subsequent reinfection of treated managed colonies (Kraus, 1995). Evidence from other countries (Kraus 1995; Somerville and Rural Industries Research and Development Corporation (Australia). Honeybee Research and Development (Program). 2008) suggests that established wild colonies numbers are reduced by 75% to 90% following the introduction of *Varroa destructor*, an external parasitic mite of honeybees.

What role wild colonies play in the spread of Varroa, and what the effect will be of their elimination depends primarily on their current spatial distribution. However, relatively few quantitative studies have been done on wild colony distributions and each study has concentrated on a relatively small geographic area.

Table 1 Listing of all quantitative wild *Apis mellifera* studies in Australia

Date	Reference	Location	Sampled areas	Total hectares	Total km2	Number of colonies
March - April 1993	(Oldroyd et al., 1997)	Wyperfeld National Park, Victoria	Creek frontage	25	0.25	45-80
December - April 1995	(Goodman and Hepworth, 2004)	Goulburn valley, Victoria	Roadside strip, river frontage, other	90	0.9	82
April - May 2003	(Goodman and Hepworth, 2004)	Box-ironbark forests, Victoria	Forest, roadside strip	35	0.35	1
Not yet known	(Paton, 1996)	Cromer Conservation Park	Open woodland	15	0.15	6
Not yet known	(Paton, 1996)	Scott Conservation Park	Open woodland	9	0.09	1
Not yet known	(Paton, 1996)	Ngarkat Conservation Park	Mallee-heath	3600	36	4
Not yet known	(Paton, 1996)	Mt Rescue Conservation Park	Mallee-heath	2000	20	7
Not yet known	(Paton, 1996)	Flinders Chase Conservation Park	Mallee-forest	200	2	45-80
1992	(Manning, 1992)	South-west corner, Western Australia	Not yet known	Not yet known	Not yet known	Not yet known

To further illustrate this point, there are 7,716,000 hectares (Department of Sustainability and Environment, 2006) of native forest in Victoria. The area sampled for wild populations thus represents only 0.002% of this forested area.

Bee movements

Each colony has a normal foraging range of 4km (Seeley, 1995) from their nest site. This range has been deduced by interpreting the dance language of the honeybees. The range implies that in areas where the average colony density is greater than 0.00025 colonies/hectare competition for floral resources between colonies occurs. The relative abundance of these resources within a foraging range determines the population density that an area can sustain. However, climatic and seasonal effects will also impact colony densities.

There are numerous ways in which bees from different colonies interact, and thus can transmit pests or diseases between colonies. When a colony is weakened due to ill health, bees from other colonies will detect this and mount raids on the weakened colony’s honey reserves. The weakened colony will not be able to effectively defend itself, but the bees instigating the robbing may be exposed to the threat agent. Within an apiary, the large number of hives also means that bees sometimes get disoriented and land at the entrance of hive other than their own. If they are carrying food or water they are generally admitted to the other colony’s hive.

In terms of expanding their range, bees are known to swarm in the early spring; a large proportion of the colony leaves in search of a new home. If the entire colony swarms, this is referred to as absconding. Management practices lessen the likelihood of this occurring in managed colonies, but it is a frequent occurrence in wild colonies.

Finally, the act of mating necessarily brings the queen of a given colony into contact with drones (males) from other colonies. Queen mating occurs at a range beyond that of normal foraging.

Pests and diseases

There are a number of endemic diseases and pests of honeybees in Australia. From a spatial epidemiology perspective, of more interest are the exotic diseases and pests. Whilst the obvious entry point for an exotic disease or pest is via a port or airport, it is also possible to send live bees through the mail (both legally and illegally) and these bees may provide the vector for transmission.

The most significant threat to the Australian honeybee industry is an external parasitic mite known as *Varroa destructor*. All major honey producing countries have this pest, with the exception of Australia.

Varroa destructor is naturalised to the Asian honeybee, *Apis cerana*. *Apis cerana* is itself a potential exotic threat to the Australian honeybee industry as it not only serves as a reservoir for exotic diseases and pests but may also out-compete *Apis mellifera* in certain areas (Anderson, 2008). Since 2007, the Department of Primary Industries in Queensland have been attempting to contain an incursion of *Apis cerana* in Cairns (Christie, 2008).

The other exotic pests of significance are also mites; the Tracheal mite *Acarapis woodi* and the Tropilaelaps mite *Tropilaelaps clareae*. There is also recent evidence from Papua New Guinea that another Varroa species, *Varroa jacobsoni*, has now naturalised to *Apis mellifera* and thus this strain will also pose a threat.

Biosecurity arrangements

A biosecurity strategy may be comprised of policies and procedures governing the following:

- Surveillance
- Sampling – pre and post-detection
- Quarantine zones and movement controls.

There are three possible goals of a biosecurity strategy:

- Eradicate an introduced threat
- Minimise the geographic spread of an introduced threat
- Minimise the (long-term economic) impact of an introduced threat.

Each point may require a different set of policies or procedures.

The current biosecurity policy for the Australian honeybee industry is outlined in AUSVETPLAN (Animal Health Australia, 2008). In brief, it comprises the following:

- Surveillance – pre-detection; 27 sentinel hives centred around ports and airports, monitored quarterly (some locations twice per year).
- Surveillance – post-detection; identification of managed and wild colonies within restricted area (RA)
- Sampling – pre-detection; only sentinel hives
- Sampling – post detection; not specified
- Quarantine zones:
  - restricted area (RA) of 25km radius around infected premises (IP)
  - all-other apiaries owned by beekeeper quarantined and inspected
  - dangerous contact premises (DCP) determined via movement tracing
  - larger control area (CA) determined by Chief Veterinary Officer (CVO)
  - movements within CA permitted, but not outside CA without CVO approval.

The *Varroa destructor* incursion in New Zealand

Varroa destructor was first detected in the upper North Island of New Zealand in April 2000 (Sanson, 2007). Subsequent analysis indicated that despite a sampling program of 400 hives per annum in high risk areas, Varroa may have been present for up to 3 years before detection (Goodwin, 2008).

Movement restrictions were immediately implemented, and analysis was done to determine whether eradication was possible. Sanson explains the outcomes of this analysis:

> “Following extensive technical advice and industry consultation, eradication was not attempted in the North Island. Instead, a control programme, based upon strategic use of miticide strips

> and the formation of a buffer zone incorporating movement controls, was implemented. All exports of hives, queen bees and other risk goods to the South Island had been banned immediately after initial detection in April 2000, in an attempt to curtail transmission opportunities to the South Island, which was believed to be free of the pest. Tracing high-risk movements of bees and associated equipment to the South Island had not found any evidence of spread.
>
> To confirm the mite-free status of the South Island, a surveillance programme was designed and conducted during the autumn (March–May) of 2001, 2002 and 2003. The design of the surveillance programme was based on two key objectives, viz if the mite was absent, then 'proof ' of freedom should be established according to Office International des Épizooties (OIE) guidelines, which proposed that surveys for freedom from bee diseases should be designed to detect a prevalence not exceeding 0.2%, with 99% confidence. However, if Varroa were present, it should be detected at a sufficiently early stage such that an eradication attempt would be feasible. It was felt that if the mite was present, and still confined within a single cluster of up to 20 x 20 km in size, that eradication could be achievable." (Sanson, 2007)

The buffer zone, which utilised natural geographic boundaries proved successful at slowing the spread of Varroa but by 2003 it had been found near Wellington on the southern end of the North Island. The cause of the breach was suspected to be a logging truck carrying an infected colony (Goodwin, 2008). In 2007, Varroa was detected in the South Island, where the sampling program (Sanson, 2007) had identified the incursion early enough to attempt elimination. However, a political decision not to attempt eradication was made, and Varroa spread further through the South Island. In September 2008, the Ministry of Agriculture and Forestry (MAF) revoked all movement controls, declaring "*The infestation in North Canterbury is now beyond the point where it can be eradicated or contained in a localised programme. In addition, the high densities of hives in the Canterbury region and the lack of geographical barriers means there is little scope for an effective movement control line to progressively withdraw down the South Island*" (Hamblyn, 2008).

The purpose of models and simulation

Models have been used throughout science for a long time, the advent of computers has led to the development of a specialised field of modelling involving computer simulation. Much has been written on the purpose and value of computer simulation models, and how they are used in both science and society generally.

Keeling identifies two distinct roles for models; *prediction* and *understanding* (Keeling and Rohani, 2008). Axelrod identifies these same two roles (and five others), but labels "understanding" as "discovery" (Axelrod, 2007) and states "*the use of simulation for the discovery of new relationships and principles is at least important as proof or prediction*". The problem plaguing predictive models is typified by work of Lorenz in the 1970s when he observed the weather system he was analysing exhibited the properties of a chaotic system (Lorenz, 1995). A chaotic system is a dynamic system in which small changes to the input conditions create exponentially magnified changes in the output dynamics, giving the appearance of randomness. Even by following the rather ambitious instructions of Keeling and ensuring our predictive model "is as accurate as possible and therefore includes all of the known complexities and population-level heterogeneities" (Keeling and Rohani, 2008), stochastic and chaotic effects ensure that predictive outcomes cannot be guaranteed.

In a report commissioned by the United Kingdom government's Department for Environment, Food and Rural Affairs following the Foot and Mouth Disease epidemic of 2001, Taylor comments on the use of models as a communication tool:

> "Models can also be an important aid to communication. They can help in explaining complex and often difficult aspects of system behaviour to 'non-experts', especially if the models can produce graphical visual, even animated, outputs. However, the very fact that such graphical outputs can be persuasive may also be a danger if the limitations of a model are not

> appreciated, or, indeed, if a model is fundamentally flawed. The output, by its very nature of consisting of numbers and charts can appear deceptively certain." (Taylor, 2003).

Thus the use of models by policy makers can indeed be counter-productive. Taylor further goes on to identify two distinct epidemic modelling situations "in which policy decisions are required:

> 1. contingency (strategic) planning– 'standing' policy made in 'peacetime' which details the strategies to be followed in the event of future outbreaks;
>
> 2. tactical decision making during an epidemic ('wartime') – reactive decisions to adjust control measures in response to unfolding events.
>
> One problem in 2001 was that the distinction between these two types of decision became blurred. The epidemic rapidly attained a scale unforeseen by the existing contingency plan so that new strategies had to be developed in response to the deteriorating situation. Furthermore, the lack of an adequate veterinary intelligence system meant that these new strategies were made and decided upon with the support of models based on incomplete data, using simplifying assumptions to fill in the gaps. In truth, models were simply the tool used to analyse the data, but the novelty of this analytical tool to decision makers at the time and the nature of model outputs to appear more certain than perhaps they are, meant that the boundary between data and assumption was overlooked." (Taylor, 2003)

Beyond the need for well-practiced science, there is a therefore a strong need for quality assurance in any model from which inferences will be drawn and implemented as policy. Quality assurance for models generally takes the form of:

- verification
- validation
- calibration
- sensitivity analysis.

There is much discussion (and confusion) in the literature about the use of terms "verification" and "validation" (Rykiel, 1996), and philosophical arguments exist as to whether they are even possible (Oreskes, 1994). For the purposes of this research, the definitions used will be those provided by Rykiel, namely:

> "Verification is a demonstration that the modeling formalism is correct…Validation is a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model." (Rykiel, 1996).

Objectives

The total value of the pollination services provided for honeybees for Australian agriculture is estimated at $2.1 billion. Within Australia, it is exotic pests such as *Varroa destructor* that most threaten crop pollination due to the effect that they will have on wild and managed *Apis mellifera*. My hypothesis is that it is possible to develop a spatio-temporal system model using agent based modelling to predict the economic impact on crop pollination due to the introduction of a threat agent. This model would lead to the development of a least economic impact control strategy when (and where) such an event occurs.

Methodology

Epidemic models

In order to understand whether disease transmission will result in an epidemic, Diekmann and Heesterbeek suggest following a "three-step procedure:

- Model the contact process.
- Model the mixing of susceptibles and infectives; that is, specify what fraction of the contacts of an infective are with a susceptible, given the population composition in terms of susceptibles and infectives.
- Specify the probability that a contact between an infective and a susceptible actually leads to transmission" (Diekmann and Heesterbeek, 2000 p.3-4).

Modelling of the contact process has been an area of focus for much recent epidemiological research. Newman et. al. note that "traditional epidemiological models almost all make use of the so-called 'fully-mixed' approximation, which is the approximation that transmission is equally likely between any pair of individuals in a population or subpopulation" (Newman et al., 2006 p. 417). Stochastic models fare somewhat better, being able to model this contact as a random variable. A contact network model restricts contact between individuals (nodes in a graph) to only be possible via contact links (edges in a graph). Recent research has focussed on the properties of epidemic spreads on graphs having random (Gabriel et al., 1990), lattice (Rhodes, 1997), small-world (Moore, 2000) and scale-free properties (Pastor-Satorras, 2001). The mathematical techniques used to analyse dynamic processes on such networks include percolation theory (Grassberger, 1983) and mean-field theory (Kleczkowski and Grenfell, 1999), both originating from statistical mechanics. However, computer simulation remains an attractive option as it allows an extension of results from synthetic landscapes to actual landscapes incorporating geographic information. Conversely, any geographical landscape may also be modelled as a network for analysis (Herrmann, 2003). The simulation constructs typically applied to epidemiology include cellular automata and agent-based modelling.

Patterns of movement

A particular focus of my research has been on examining the effects of patterns of movement in epidemiology models. Movement can be characterised as occurring at different scales of time and space. In most epidemiological models, patterns of movement are implicitly considered in analysis of the contact process rather than explicitly examined. Exceptions occur in the study of epidemics using cellular automata where random movements (Boccara and Cheong, 1993), long-range link swapping (Belykh et al., 2004), and two-state circulation (Ahmed and Elgazzar, 2001) are analysed. Boccara and Cheong (Boccara and Cheong, 1993) conclude that even in their self-described crude model, the importance of motion is emphasised in their results.

Movement in geographical space is generally goal-orientated. Categorisation of the movements of people (Bell and Ward, 2000; Prothero and Chapman, 1985) and animals (Dingle, 1996) reveals factors in common; movements among a population occur across a range of distances and timeframes. Quantitative data (Bell, 2004; Reades et al., 2007; Zandvliet and Dijst, 2004) suggests that for a human population there is a distribution of different movement types occurring simultaneously.

Dingle defines a taxonomy of movement, including such terms as foraging, commuting, ranging and migration (Dingle, 1996). Beekeepers in Australia often describe themselves as either nomadic or migratory. Dingle's definition of migration is that it comprises "*undistracted movement (with)* *responses to resources/home range (either) suspended or suppressed*" (Dingle, 1996). Thus the beekeepers idiomatic use of the term "migration" to describe their movements aligns with the scientific definition.

Other types of movement defined in the literature include random walks and Levi flights. Where multiple individuals are on the move simultaneously, terms such as flocking, herding, converging and diverging are often used to describe population-level movement patterns.

Agent Based Modelling

Agent Based Modelling (ABM) is a term applied to models where multiple autonomous agents interact with one another and their environment, and the collective agent behaviour constitutes simulation of the system being modelled. The agent's behaviour is defined by a set of rules, and the simulation progresses through iterations representative of discrete time intervals. In each iteration, the state of each agent is updated in accordance with the behavioural ruleset, and thus the state of the system is updated as a consequence.

In this manner, ABM is a naturalistic approach to modelling many societal phenomena where each agent takes the role of an individual human. However, the concept of an agent does not necessarily need to correspond to either a physical or sentient entity. The essential characteristic that defines an agent is instead autonomy (Batty, 2005). Thus the general question that ABM is designed to answer, as expressed by Epstein is "*How could the autonomous local interactions of heterogenous bondedly rational agents generate the given regularity?*" (Epstein, 2006).

ABM's precursor is the modelling paradigm of Cellular Automata (CA). Both are capable of modelling spatio-temporal phenomenon at a system level by defining rulesets at either an individual or cellular level. What distinguishes ABM from CA is that agents are free to move through the modelled space, whereas the cells in CA have a fixed location and a defined set of neighbours for the duration of the simulation. This gives agents the freedom to break existing relationships and form new relationships as they move through the model space. Again the temptation exists to anthropomorphise agent concepts; the relationships do not necessarily imply any consciousness on the part of the agent. For instance, a spatial epidemiology model developed using ABM may define proximity within a certain range to constitute a "contact" relationship for possible disease transmission.

The model space can be either continuous or discrete and there is no restriction on the number of dimensions, although as a representation of an actual system either two or three dimensions tend to be used. The space itself can take the form of shapes that do not have any physical analog; for instance, a toroidal shape is often used to exclude edge effects. In some sources, a specific distinction is drawn for models where the space represents a geographic space, and the resulting models are referred to as Geographic Automata Systems (Benenson and Torrens, 2004). To further confuse matters, the term Multiagent System (MAS) is often used interchangeably with ABM (Benenson and Torrens, 2004).

ABM is implemented in software, and in that respect there is a natural equivalency between agents and software objects. Several toolkits are available for creating models, although many of the packages used in the literature are no longer under active development having been replaced by newer toolkits. Three commonly used and current toolkits are Repast (Argonne National Laboratory, 2008), NetLogo (Wilensky, 1999) and MASON (Luke, 2005).

Honeybee epidemiology – the modelling challenge

There are significant challenges in attempting to build a bottom-up model of the honeybee industry in Australia, due largely to the scarcity of data needed to model spatio-temporal distributions of managed and wild colonies.

Underlying this difficulty is unpredictability in the flowering of the main Australian honeybee resource; eucalypts. Birtchnell has found that for melliferous (honey-producing) eucalypts, the period between flowering for different species can range from 1 to 7 years, and that most species flower once every 2 to 4 years (Birtchnell and Gibson, 2006). A further challenge is to account for inter and intra-region variations. For example, the same species tends to flower earlier in more northerly locations, but within a given forest only a proportion of the population may flower in a given year. To the extent that they can be predicted, the main input is rainfall (Birtchnell et al., 2008), and this is monitored on an ongoing basis by beekeepers to assist in planning. The eucalypts response to rainfall is to set buds, and a period of rain may thus result in a flowering event from 2 months to 18 months later, depending on the species in the area receiving rain. Thus if the distributions of each eucalypt species can be established, it is possible to use rainfall to predict a plausible sequence of eucalyptus flowering attractor events. Unfortunately, preliminary work has identified significant discrepancies between sources on the distribution of key melliferous eucalypts (Brooker and Centre for Plant Biodiversity Research., 2002; Brooker and Kleinig, 2006; Clemson and New South Wales. Dept. of Agriculture., 1985; Goodman, 1973; Nicolle, 2006) which creates a further modelling challenge.

As state regulations require the registration of apiary sites on crown land, no record of apiary sites on private land is held except by the individual beekeepers. Beekeepers are reluctant to share this information as it is used to gain a competitive advantage. Additionally, there is no requirement to report on hive movement between apiary sites (either public or private) except retrospectively in the event of an incursion, where this information is obtained by questioning beekeepers directly. Finally, it is reasonable to expect that hive movements are influenced by the home locations of a beekeepers residential property, whereby closer sites are preferred to more distant sites. Whilst residential data is gathered through state government beekeeper registrations, it is not in the public domain.

Putting aside the challenge of gathering data on managed hive locations and movements which would in theory be possible with full co-operation from beekeepers and governments, there is the challenge of obtaining information on wild colony distributions. As highlighted in the Introduction, there is very little data available on wild populations of *Apis mellifera* in Australia. The validity of drawing inferences about distributions from existing data alone is questionable, and thus further delimiting surveys may be required to support spatial analysis and model development.

Finally, although *Varroa destructor* is now widespread amongst all other major honey producing countries, there is very little epidemiological data available with the possible of exception of New Zealand. However, the dissimilarity between New Zealand’s beekeeping flora and industry model means that considerable analysis will need to be done in order to derive results that may be applicable in an Australian incursion of Varroa.

Determining a distribution of wild colonies throughout Victoria

Key to understanding the likely spread of disease and pests amongst managed colonies is the relationship these managed colonies have with wild colonies. Wild colonies can act as a reservoir for disease and re-infection of managed colonies (Morse et al., 1990; Spiewok et al., 2008). Wide scale eradication of wild colonies in response to an incursion is unlikely to be economically feasible in Australia (Oldroyd, 1998; Taylor, 2007). Wild colony densities following the introduction of Varroa are expected to fall drastically (Chen et al., 2006; Kraus, 1995) but it is probable that wild colonies will still play a role in the spread of the pest before succumbing.

Wild colony densities vary in accordance with the level of resources available in the environment. This means that colony densities vary not just across space, but also across time. Field studies are required in order to understand the density of colonies across a large geographical area. The results should then be interpreted in the context of the level of resources available in each of the sampled areas. To determine the level of resources available requires an analysis of the geographical area surrounding the sample location, and the conditions in that area over the preceding two years. A model of how wild colony densities vary in accordance with differing levels of resources in the environment can then be constructed.

Results

The phenomenon of attracted movement, whereby large numbers of beekeepers are drawn to "attractor" events such as almond pollination, have been shown by modelling to have a significant effect on the spread of diseases. Such attractor events occur over a relatively small, defined area for a relatively short duration of time. These events could serve as a potential staging ground for interventions aimed at controlling disease spread.

During the course of a normal beekeeping season, beekeeper seasonal movements have been shown to be highly complex and difficult to model accurately. The success of a beekeepers' operation depends on his/her ability to optimise hive movements in a way which maximises production and at the same time minimises travelling costs. Beekeepers intuitively solve complex optimisation problems that are taxing even for powerful computers. Rather than model beekeeper movements, a better approach would be to use actual movement data if this were available under a system such as the Australian National Livestock Identification System (NLIS).

Across a wide scale survey of wild colonies across Victoria, colonies were found at similar densities in areas ranging from Wyperfeld National Park in the west to Marysville (after the bushfires) in the east. New techniques to improve the analysis of the wild colony surveys were developed, and these are currently being applied to construct of model of the wild colony distribution across Victoria.

The original intention of developing a spatio-temporal model to test potential control strategies has not been met. In the case of honeybee disease and pest spread, there are too many variables and too many unknowns to make reasonable inferences. A reasonable attempt to address the limitations of current knowledge could be made through further research. Please see the section on recommendations for further details.

Implications

A multitude of threats exist to the honeybee industry with the potential to impact both honey production and more significantly, agricultural and horticultural crop pollination. The most significant of these threats in Australia is *Varroa destructor* (Monck 2008), an external parasitic mite of honeybees. Experiences with the introduction and spread of Varroa in New Zealand since 2000 (Stevenson et al. 2005) suggest that it is unlikely that Australia will detect a Varroa incursion in time to attempt eradication, and that the spread of Varroa throughout Australia will not be possible to stop.

Australia faces additional challenges with a Varroa incursion, beyond those encountered in New Zealand:

- much larger geographical area and coastline to monitor through surveillance programs
- more frequent and longer range hive movements
- no natural geographic quarantine boundaries in eastern states
- large self-sustaining wild honeybee population
- potentially different policy responses in each individual state or territory
- larger potential impact on horticultural and agricultural industries.

Current biosecurity control strategies, particularly AUSVETPLAN (Animal Health Australia 2008) have been reviewed in recent workshops held with key stakeholders (Turner, 2010). Further work to examine the impact of varying strategies or parameters from those outlined in AUSVETPLAN, as well as the efficacy of hypothetical technology-based improvements in hive movement tracing, beelining and wild colony eradication would provide additional valuable information to the honeybee industry that could be used in longer term planning for incursion responses.

There are possible reasons why current biosecurity arrangements may perform poorly, but the relative and quantitative importance of these are not understood. Some of these include:

- Failure to detect outbreak in a timely manner
- Inaccurately delimiting initial extent of outbreak
- Inability to eliminate or mitigate risk posed by wild populations
- Inability to regulate movement of other materials and vehicles through restricted area (e.g. logging trucks)
- Beekeeper non-compliance
- Delayed, inaccurate and labour intensive hive movement tracing
- Insufficient resources or budget to cope with the scale of the outbreak.

Recommendations

The RIRDC project “A Geographic Flowering Calendar Using Dynamic Data from the World Wide Web” will provide valuable additional data which can be synthesised with the results of current PhD research to improve the model developed of wild honeybee population distributions.

However, understanding beekeeper hive movements at an industry-wide level remains a key challenge to developing a model of disease and pest spread. Mandatory introduction of a scheme such as the National Livestock Identification Scheme (NLIS) to the beekeeping industry would enable the relevant data to be acquired and analysed. However, the costs and benefits of such a scheme are not currently fully understood. For this reason, one recommendation of the research undertaken in this project is that RIRDC consider a trial of a hive tracking scheme across two seasons with a small group of large-scale commercial beekeepers. This idea has been discussed previously with both beekeepers and scientists within the industry. The data collected would enable new analytical techniques to be applied, new models of beekeeper movements to be developed and facilitate a cost/benefit analysis of an industry wide hive movement tracking scheme.

Appendix: The benefits of the top-up scholarship

Through their generous assistance in the form of a top-up scholarship, RIRDC have played a key role in enabling the author to return to fulltime study and undertake the research forming the basis of the author's PhD candidature.

The scholarship has allowed the author to attend and present my work at conferences and workshops both in Australia and internationally. Conferences at which I presented have included:

- Apimondia International Congress in Montpellier, France
- COSIT in Aber Wrach, France
- Geocomputation in Sydney, Australia
- GIScience in Park City, USA
- 2011 Victorian Apiarists Association Conference in Bendigo, Australia
- ARCRNSISS "Methodology, Tools and Techniques Forum" workshop in Newcastle.

Other conferences attended included:

- Almond Board of Australia Conference in the Barossa Valley, Australia
- Victorian Apiarists Association Conference in Mildura, Australia
- FOSS4G: Free and Open Source Software for Geospatial in Sydney, Australia.

The scholarship has also enabled the author to attend training as a beekeeper, which proved invaluable for enabling the author to conduct fieldwork. The training was undertaken through the Bendigo Regional Institute of TAFE.

Furthermore, research materials were purchased from scholarship funds including books, hardware and specialist software (e.g. ENVI, a program which costs US$1,250).

Finally, the scholarship made possible the field research undertaken in late 2009, and covered expenses such as food, petrol and accommodation.

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Understanding the Spread of Honeybee Pests and Diseases

by Jonathan Arundel

Publication No. 11/102

This research focused primarily on an attempt to develop an agent-based model of both managed and wild honeybee colonies and their movements. The purpose of this model was to understand both the spread of honeybee diseases and pests, and the effectiveness of strategies to minimise this spread.

This report will be of interest to scientists, policy makers and government agencies responsible for managing biosecurity.

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