Ministry for Primary Industries
Manatū Ahu Matua

Impact of climate change on crop pollinator in New Zealand

MPI Technical Paper No: 2013/30

Prepared for the Ministry for Primary Industries
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ISBN No: 978-0-478-42044-9
ISSN No: 2013/30

September 2013

New Zealand Government

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Contents

Page

Executive summary **1**

1 Introduction **3**

2 Methods **6**

2.1 Pollinator Abundance 6
2.2 Onion and pak choi 6
2.3 Onion observations: 7
2.4 Pak choi observations: 7
2.5 Carrot, radish and white clover: 8
2.6 Pollinator behaviour 8
2.7 Key pollinating species 9
2.8 Data collection 10
2.9 Data analysis 11

3 Results **12**

3.1 Overview of Pollinators across five crop species 12
3.2 Pak choi and onion 14
3.3 Weather variables 15
3.4 Relationships between flower visitor abundance and weather variables 18
3.4.1 Temperature 18
3.4.3 Radiation 20
3.4.4 Wind speed 21
3.4.5 Total pollinator abundance 22
3.4.6 Diversity 23
3.5 Pollinator behaviour 25
3.5.3 Observed taxa 26
3.5.4 Temperature and pollinator behaviour 27
3.5.5 Other climatic variables and pollinator behaviour 27

4 Discussion **29**

4.1 Pollinators of New Zealand seed crops 29
4.2 Pollinator abundance and time of day 29
4.3 Pollinator abundance and climate 29
4.4 Pollinator diversity, total pollinator abundance and climate 31
4.5 Pollinator behaviour and climate 31
4.6 Crop pollination and climate change 32
4.6.1 Canterbury 33
4.6.2 Tasman 33
4.6.3 Hawke's Bay and Gisborne 33
4.6.4 Bay of Plenty 34
4.6.5 Northland 34
4.6.6 Otago 34
4.7 Limitations of the study 34
4.8 Climate change and pollinator-crop interactions: Future Research 35

5 Conclusion **37**

6 Acknowledgements **38**

7 References **39**

APPENDIX 1 Projects which provided data towards this report **43**

FRST C02X0221 The role of indigenous pollinators as New Zealand specific mechanisms for transgene flow 43

Specific mechanisms for transgene flow 43

SFF 05/122 Code of practice for managing pollination of vegetable seed crops 44

SFF 07/035 Sustainable pollination of seed crops in the presence of varroa; where to from here? 44

APPENDIX 2 Pollinator Behaviour and climate variability **46**

APPENDIX 3: Project Plan, Current and Future Outputs **48**

APPENDIX 4: Popular Report Summary **52**

Executive summary

Insect pollinated seed crops contribute at least NZ$60Million annually in export earnings. These crops are pollinated by a range of insects including honey bees, bumble bees, native bees and flies, and maintaining pollinator diversity can be important for maximising crop yields. However, different pollinators are active at different times of the day and under varying climatic conditions (activity windows). Climate change may impact pollinator activity windows by altering foraging periods and also their behavior (e.g. time spent on flowers and distances moved within and between plants).

The aim of this programme was to test the hypothesis that pollinator activity windows differ with changing climate (specifically a 4^{o}C increase in temperature, but also humidity, light intensity and wind). This leads to altered:

1) pollinator abundance and diversity
2) pollinator behaviour and movement

To assess whether changing climate influences pollinator activity windows, thereby altering pollinator abundance and diversity we used an existing dataset comprising some 85,000 individual observations collected across a number of important annual seed crops, especially the brassica pak choi (open pollinated) and F_1 hybrid onions, across both North and South Islands, combined retrospectively with weather data for each site.

To assess whether changing climate influences pollinator activity windows, thereby altering pollinator behaviour and movement we collected further data on behavior of insect pollinators on the crops to supplement and extend an earlier dataset. Previous New Zealand studies indicated that a relatively small assembly of insects is dominant in abundance and a smaller subset of these provide the majority of pollination services to these crops. Six key pollinator species (honey bees, bumble bees and four species of fly) were monitored as individual insects for foraging behavior on flowers as well as frequency and distance of travel between flowers. Weather data were collected on site for the new dataset.

Honey bees were found to be the most abundant pollinators within the crops examined. This was not surprising since beehives are generally introduced to the crops, while other insects are present as part of the landscape insect abundance. The requirement of hybrid seed crops for cross-pollination requires the movement of pollinators between male fertile and sterile plants which are normally grown as separate rows. This restricts the relative value of some of these pollinator species since some species express strong floral constancy to a hybrid type (ie will forage on just one hybrid line).

Apart from a few species-specific anomalies, changes in climate variables (particularly temperature) were found to affect pollinator activity windows leading to a change in pollinator diversity and abundance. These data confirmed a relationship between temperature and insect pollinator activity on crops, with time of day superimposed for honeybee activity. Other climate variables (e.g. relative humidity and light intensity) also showed relationships with some taxa; however, there were strong correlations between climatic variables themselves. Therefore, it was not possible to determine the level of direct influence each climatic variable contributed to each insect taxa.

A key feature of the insect activity is the increased relative abundance of flies and bumble bees at the lower temperatures (<15^{o}C) compared to honey bees. Peak pollinator diversity across species and crops tended to occur in the 20–25^{o}C range, but above this range honey bee abundance increased relative to other pollinating species. Low relative humidity (<RH50%) was more associated with higher honeybee abundance and a few fly species were particularly abundant at higher humidity (>RH80%).

Time of day, independently of other variables, influenced insect abundance on these crops. Overall abundance was strongly dominated by honey bee presence in the middle of the day, but two fly taxa (Seedcorn and Ephydrid flies) showed a strong preference for activity in the 6–8a.m. and 4–9p.m. periods of the day.

Changes in climate variables (specifically temperature) were also found to affect pollinator activity windows leading to a change in behavior. This was demonstrated by a general increase in the rate of stigma contacts at higher temperatures by all six pollinating species assessed. However, changing climate did not correspond with changes in movement between inflorescences. Overall, these finding verify the hypothesis with exception that changing climate leads to changes in pollinator movement.

Climate change predictions for regional New Zealand over the remainder of the century suggest a marked increase in number of days which exceed 25^{o}C and reduced rainfall in some regions could see lower relative humidity. These conditions should affect the activity windows of honey bees leading to increased abundances and an extension of foraging time. However, climate change forecasts also predict an increase in extreme weather events such as droughts and floods in New Zealand. Such events could significantly impact honey bee pollination. To reduce the potential impact of increased climate variability on crop pollination, management strategies should focus on building pollinator diversity by encouraging pollinators that are active across highly variable and changeable climatic conditions. Although some preliminary research has been conducted on native bee nesting preferences and providing conditions suitable for them, very little research has been conducted on the more important fly species biology or means of ensuring abundance on crops. This is potentially important for these annual seed crops as their siting in the cropping landscape varies annually to fit crop rotation and isolation distance requirements.

Assuming climatic conditions remain suitable for growing the crops in their current regions this programme suggests that we take cognizance of the likely increased reliance on the currently vulnerable honeybee for pollination purposes. Taking steps now to better understand what drives abundance of currently unmanaged species, especially flies and native bees, aiming to find a practical solution to ensuring their presence in suitable numbers for pollination requirements, is a definite step that industry can take. This will provide benefits now as well as into the future, particularly for securing pollination services to the more valuable, but insect pollinator challenging, F_1 hybrid crops.

1 Introduction

Insect flower visitors play a vital role in pollination of many crop plants (Cunningham et al. 2002; Free 1993; Westerkampe & Gottsberger 2000), contributing an estimated 9.5% to world agricultural production used for human food (Gallai et al. 2009) and at least $2B NZD annually to the New Zealand economy [production (Ministry for Agriculture and Forestry 2010; Plant & Food Research 2009) multiplied by insect pollinated crops and pasture plants (Cunningham et al. 2002; Free 1993)]. Although climate significantly influences pollinator abundance and effectiveness, knowledge of the potential impact of climate change on crop pollination remains very limited (Kjohl et al. 2011). This lack of knowledge must be addressed to develop appropriate adaptation strategies for industries reliant on insect pollination services for crop production.

Recent studies demonstrate that a diversity of currently unmanaged pollinators contribute significantly to crop pollination (Klein et al. 2003; Rader et al. 2012; Winfree et al. 2007; Winfree et al. 2008). In New Zealand, unmanaged bee species and flies are common crop flower visitors (Howlett et al. 2005; Howlett et al. 2009; Macfarlane & Ferguson 1984; Rader et al. 2009) and are capable of contributing a higher proportion of the crop pollination service than honey bees for specific crops (Rader et al. 2012). Besides honey bees, common crop pollinating insects in New Zealand include, Bumblebees, native bees from the genera *Lasioglossum* and *Leioproctus* and flies from the families Syrphidae, Calliphoridae and Bibionidae (Rader et al. 2009). They visit the flowers of a variety of crops including brassica (Howlett et al. 2011; Rader et al. 2011; Rader et al. 2009; Rader et al. 2012), onion (Howlett et al. 2005), kiwifruit (Macfarlane & Ferguson 1984) and are common throughout New Zealand's cropping regions (North and South Islands) (Howlett et al. 2009).

Despite a lack of research into the potential influence of climate change on crop pollinators, changes in climatic variables may influence pollinating species differently. This influence can affect the window of pollinator activity in two ways: first, by influencing the abundance and diversity of pollinators on crops; and second, by altering pollinator behaviour.

Key climatic variables that influence or are correlated with the activity of pollinating species include temperature, humidity, light intensity, solar radiation and wind speed (Abrol 2010; Sarangi & Baral 2006). However, different pollinators can respond to these variables differently. For example, Bumblebee foraging can start and peak at temperatures lower than honey bees (Zhao et al. 2011). Honey bees maintain a fairly constant thorax surface temperature (33.7–35.7ºC) at air temperatures between 10-27ºC (Kovac & Stabentheiner 2011), but continuous flight at ambient temperatures below 20ºC increases the risk of thoracic temperature slipping below the minimum required for flight (Esch 1976). Bumblebees tend to have large body mass and are well insulated with long and dense setae (Heinrich 1974), allowing them to retain heat when foraging in cool conditions (Peat et al. 2005). However, this can lead to overheating in warmer conditions (Peat et al. 2005).

In general, bee activity is often restricted by the high energy demands of endothermic flight, nest building and offspring provisioning (Corbet et al. 1993). They may also travel distances of several kilometres from their nests to forage on flowers. For these reasons, Diptera are more likely to be key pollinators of plants in colder climates (Gonzalez et al. 2009; Kearns 1992). Flies can often find shelter relatively close to crops (Bennewicz 2011), therefore requiring shorter distances of travel to nectar and pollen resources. They also tend to maintain lower thorax temperatures (Morgan & Heinrich 1987) and therefore fly at lower temperatures than bees (Heinrich 1993). Diptera often rely significantly on solar radiation to gain heat for sustained flight by perching on the ground or on flowers (Arroyo et al. 1982; Heinrich 1993).

Temperatures can be several degrees higher on the surface of petals than surrounding air temperatures (Heinrich 1993).

Along with abundance, pollinator behaviour could also be altered by climate variability by influencing movement between flowers and inflorescences. For example, for honey bees to maintain adequate thoracic temperatures for flight, they may spend time shivering (Heinrich 1993). Therefore as air temperature decreases, time spent shivering as opposed to foraging may increase. If flight muscles fall below approximately 10ºC then bees are unable to generate enough heat for flight (Esch 1988). Decreasing temperatures are also likely to affect Diptera behaviour. That is because Diptera may spend more time sun basking to absorb solar radiation to build thoracic temperatures adequate to sustain flight (Morgan & Heinrich 1987).

Differing responses by pollinating insects to climate variables may have important implications for crop pollination with climate change. This is because climate change may not only effect the overall foraging time of individual pollinators but also alter pollinator diversity. That is, pollinator assemblages may change to be represented by different numbers and proportions of pollinating species than are currently present.

Current climate change models predict that by 2100 there will be an overall warming of world climate of between 0.6°C (greenhouse gas concentration maintained at 2007 levels) and 4°C (intensive use of fossil fuels with rapid world economic development) (IPCC 2007). However, patterns may vary widely even across small spatial scales. In New Zealand climate change is expected to lead to warmer average temperatures (1°C by 2040 and 2–4°C by 2090) (Fitzharris 2007; Mullan et al. 2008), with the number of days exceeding 25°C predicted to increase in all regions with exception of Westland. For example, at the end of the 21st century, Christchurch is expected to have 20–40 extra days above 25°C (current average is 31) and Auckland 40–70 days (currently 21) (Mullan et al. 2008). Rainfall in some regions is expected to decrease and drought frequency increase (Northland, Auckland, Gisborne, Hawke’s Bay) while in other regions rainfall is expected to be heavier and more frequent (Tasman, West Coast, Otago, Southland and Chathams). Models suggest changes in wind speed to be variable throughout New Zealand; however, most eastern regions and the Waikato are expected to see a 1–10% increase in wind speeds exceeding 36 km/h by 2100. Overall, the frequency of extreme events such as droughts and floods is expected to increase in New Zealand (Mullan et al. 2008).

To evaluate whether climate change (specifically the impact of a 4^{o}C rise in temperature) is likely to affect pollinator-crop interactions in New Zealand we test the hypothesis: pollinator activity windows will differ with changing climate resulting in altered pollinator abundance, diversity behaviour and movement. We used primarily pre-existing data and some new data. We initially compared pollinator assemblages across five different arable crops using pre-existing data (Appendix 1) (combined counts of almost 85,000 individual flower visiting insects) to assess the similarity of flower visiting taxa between crops. The comparison among various crop species is necessary to assess whether the effects of climate change on pollination are likely to be crop-specific or apply across crops more generally. To assess whether changing climate might affect pollinator abundance and diversity we then compared counts of flower visiting insects within flowering pak choi and onion fields that were located across North and South Islands (FRST C02X0221) with data from meteorological stations located within 10 km of field sites (climate data obtained from NIWA national climate database). Finally, to assess whether changing climate influences pollinator behaviour and movement we observed pollinator foraging behaviour (stigmas contacted, movements between inflorescences, distances moved) within pak choi and onion fields. Climate data were collected within fields after each observation. We used a combination of behaviour data collected by FRST C02X0221 and new data collected during 2011/12. The older dataset provides a significant source of behavioural data that is replicated for a wide range of pollinating species but was not specifically collected to assess the influence of climate on behaviour. For the new dataset, we focussed on selected pollinating species with an aim to observe insects under more variable climatic conditions. Therefore, the aim of the new dataset was to gather information to assess how larger variations in climate influences pollinator behaviour. We then discuss our findings in terms of:

1. The relevance of findings across a range of crops
2. Diurnal patterns of pollinator abundance
3. The influence of climate on the abundance of key pollinators and pollinator diversity
4. How the behaviour of key pollinators may be affected by climate
5. How climate change could influence crop pollinators in regions where insect pollinated crops are grown
6. What further research is required to understand the implications of climate change on insect pollinated crops.

2 Methods

2.1 Pollinator Abundance

Pre-existing observation data on pollinator abundance and distribution (FRST C02X0221) was utilised. These data were collected from commercial hybrid onion fields and commercial and trial pak choi fields located throughout the North and South Islands (Table 1). Onion and pak choi data were collected from multiple fields across consecutive years: onion from January 2004 – January 2008 and pak choi December 2004 – December 2007. Further pre-existing data recording pollinator abundance and distribution on three additional commercial seed crop species, hybrid carrot, hybrid radish and white clover (FAR/SFF 05/122, FAR/SFF 07/035), were also utilised (Table 1).

Hybrid carrot fields located in Canterbury were observed in January 2005 (3 fields), January 2006 (1 field), December 2009 (1 field), January 2010 (3 fields) and December 2010 (1 field). Hybrid radish fields were all observed in 2006-7 (4 fields in December 2006 and 2 fields in January 2007) and white clover was observed in 2004-5 (1 field in December 2004 and 7 fields in January 2005)..

Details of the methodology describing data collection for pak choi and onion crops is presented in Howlett et al. (2009) and we therefore present a brief outline here. Methodology describing data collection for carrot, radish and white clover crops is also provided. Methods of observing pollinators varied between crops to account for the differing crop architecture (e.g. hybrid crop versus non hybrid crop, inflorescence structure and differing densities of flowering inflorescences). These are further described for each crop below.

All arthropods that were observed in a flower were counted for each sample. These observations were made to the taxonomic rank that could be reliably identified during observations, i.e. genus level for most bees, particularly the native bees and species level for most Diptera. Although counts were also conducted for Lepidoptera, Coleoptera and non-bee Hymenoptera, too few individuals were counted to assess their interactions with climate variables.

2.2 Onion and pak choi

All onion fields observed were planted for the production of hybrid seed and consisted of alternate rows of male fertile (pollen donor) plants from which seed is not normally harvested and male sterile plants from which hybrid seed is harvested. Each row consisted of the same plant type and typically ran the length of a field, while rows were spaced approximately 1 m apart. Pak choi fields consisted completely of a single plant cultivar with seed harvested from all plants. Flowering plants were typically of uniform density apart from locations where vehicle or irrigation tracks were present. Five sampling points were established per field (Figure 1). Each field was observed on a single day at a time when the crop was considered to be at peak flowering (see Howlett et al. 2009). Observations at each sample point took 10–12 min (approximately 1 h to observe all sampling points at each sampling time).

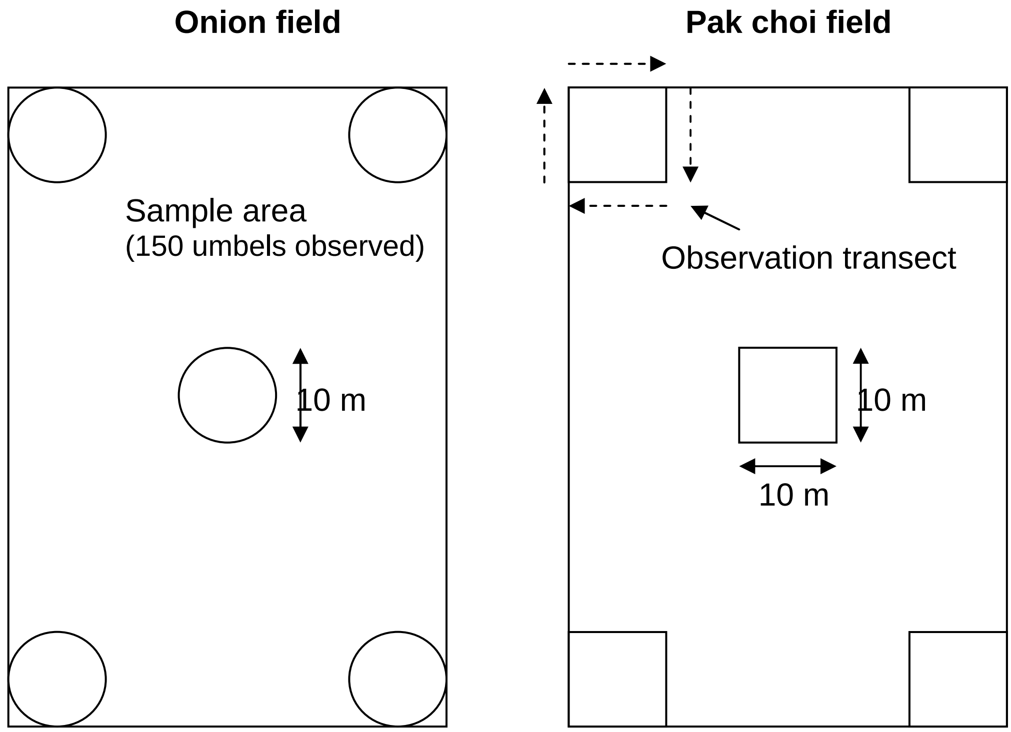

Figure 1: Observation and trapping field designs for collecting arthropod flower visitor data. Flowering onion umbels were observed inside each sampling point. Pak choi inflorescences were observed along a square 40 m transect around each sample point (Reproduced from Howlett et al. 2009 with minor modification).

Table 1: Number of fields from each region, by crop.

Region (approx. lat, long)	Onion	Pak choi	Carrot	White clover	Radish	Total
Canterbury (43º 44'; 171º 43')	14	24	11	8	6	63
Marlborough (41º 36'; 173º 52')	16	0	0	0	0	16
Southland (46º 07'; 168º 53'	0	9	0	0	0	9
Central Otago (44º 42'; 169º 15')	5	0	3	0	0	8
Wairarapa (41º 05'; 175 º 44')	8	0	0	0	0	8
Auckland (37°12'; 174°55')	0	4	0	0	0	4
Hawke's Bay (39º 39'; 176º 52')	0	3	0	0	0	3
Total	43	40	14	8	6	111

2.3 Onion observations:

In each sample area, arthropod counts were conducted on 75 male sterile and 75 male fertile flowering umbels, each containing more than 30 open flowers. Arthropod counts were made by slowly walking along each row of flowering umbels and recording individuals on a spreadsheet at the lowest taxonomic level possible. To minimize arthropod disturbance, each umbel was initially observed at a distance of 1 m. However, to record smaller arthropods, umbels were then examined at closer range (ca. 10 cm).

2.4 Pak choi observations:

For each sample area arthropod counts were conducted by walking a square transect with each side 10 m in length (Figure 1). Each transect was walked slowly to minimise arthropod disturbance and all flower visitors within a 1 m path were recorded.

Each field was visited for data collection on a single date only. On that date, numbers of insects for each species observed were recorded at 2-hourly intervals. For onion and pak choi fields observed in 2004 and Onion fields in 2005, the first set of observations was conducted at 6 am and the last set at 8 pm. The exceptions were two Wairarapa fields that were observed from 6 am through to 2 pm. All other fields were sampled at 10 am, noon, and 2 pm. In all cases, observations were conducted at all five sample points at each observation time.

2.5 Carrot, radish and white clover:

As with pak choi and onion crops, observations recording insect abundance within carrot, radish and white clover crops were conducted when the crops were considered to be at peak flower. For radish this was when open flower density exceeded 1000/m^2; for carrot, when more than 30% of the umbels contained more than 500 open flowers; and for white clover when open florets exceeded 2000/m^2.

Observations within each carrot field were conducted on 150 flowering umbels, of which 75 were male sterile and 75 were male fertile. These were observed inside each of three circular sample areas (radius 5 m), two located in opposing corners and one in the centre of each field (Figure 2). Flower visitors were only counted on carrot umbels estimated to contain more than 500 open flowers (visual estimations).

For radish and white clover, three transects were established in each field (2 corner and 1 centre transect) (Figure 2). Counts of flower-visiting arthropods were conducted by walking around each square transect of 4 x 10 m lengths in pak choi and radish fields and around a circular transect with circumference 31.4 m in white clover. For pak choi and radish, each corner transect followed along 20 m of field edge (2 x 10 m edge sides) and 20 m (2 x 10 m internal sides) inside the crop, while the corner transects for white clover reached the edge at two points (Figure 1). The centre transect in each crop species was located entirely inside the crop. Each transect was walked three times during the day at 10−11 am, 12−1 pm and 2−3 pm at a slow pace to minimise arthropod disturbance, with each transect taking 10–12 min to complete. All flower visitors within 1 m of the path were recorded.

In all cases flower-visiting arthropods were recorded within each sample area three times during the day at all onion fields and one carrot field at 10−11 am, 12−1 pm and 2−3 pm, while for the remaining carrot fields sample areas were observed once at 12−1 pm. Observations at each sample point took 10–12 min (approximately 40 min to observe all sampling points at each sampling time).

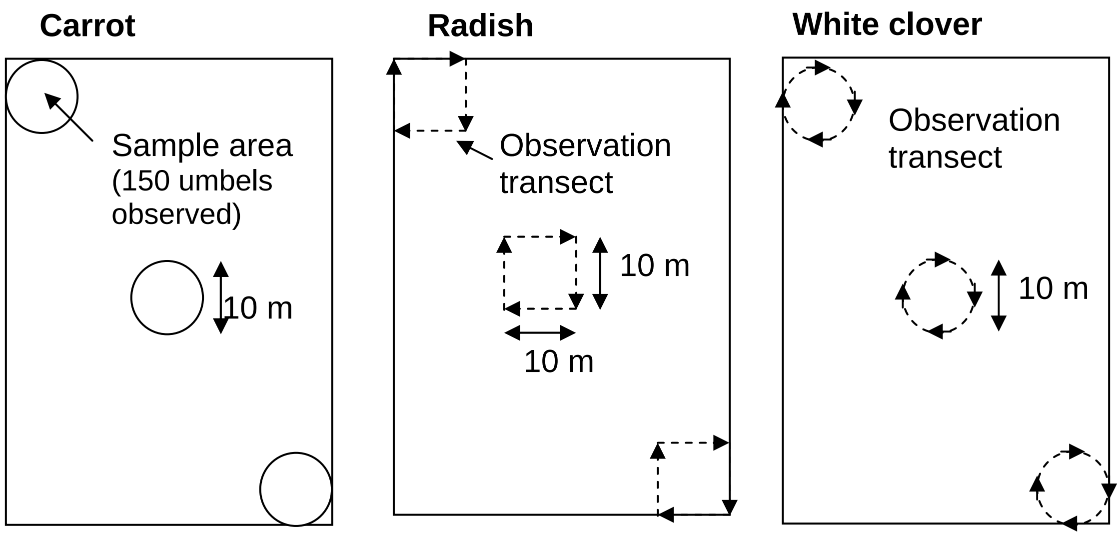

Figure 2: Field designs to assess flower visiting arthropods. Radish inflorescences were observed by walking a square 40 m transect around each sample point and white clover by walking a 31.4 m circular transect. Flowering carrot umbels were observed inside each sampling point.

2.6 Pollinator behaviour

The behaviour of six key pollinating species was collected between December 2005 and December 2007 (FRST Indigenous Pollinators Programme, FRST C02X0221) and supplemented with new data collected between December 2011 and January 2012. Methodology for monitoring pollinator behaviour was the same for both data sets; however, additional data on the distance and direction moved by individual pollinators was collected for the 2011/12 data.

2.7 Key pollinating species

Behaviour observations were focussed on two bee species: honey bees (*Apis mellifera*) and short tongued bumblebees (*Bombus terrestris*) (Figure 3); and four fly species: drone flies (*Eristalis tenax*), New Zealand black hoverflies (*Melangyna novaezelandiae*), Australian brown blow flies (*Calliphora stygia*) and European blue blow flies (*Calliphora vicina*) (Figure 4). These species are among the most common flower visitors to flowering pak choi and onion seed crops and are recognised crop pollinators in New Zealand (Howlett et al. 2011; Rader et al. 2009). In all cases (with the exception of *C. stygia*), they are physically distinctive enough to identify visually. *Calliphora stygia* is very similar to *C. hilli* in appearance and visual assessments were unable to separate the species. However, in New Zealand *C. stygia* is much more abundant than *C. hilli* (Henning et al. 2005). Moreover, Howlett et al. (2009) did not record *C. hilli* in an extensive window trap and hand netting survey within pak choi or onion crops throughout the North and South Islands(Howlett et al. 2009).This information suggests that *C. stygia* is much more likely to observed in these crops than *C. hilli*.

Halictidae, *Lasioglossum* bee (*Lasioglossum* spp.)

Colletidae, *Leioproctus fulvescens* (Smith 1876)

Colletidae, *Leioproctus* bee (*Leioproctus* spp.)

Apidae, short tongued bumblebee (*Bombus terrestris* Linnaeus 1758)

Figure 3: Common bees observed visiting seed crops.

Syrphidae, New Zealand black hoverfly [*Melangyna novaezelandiae* (Macquart 1855)]

Syrphidae, New Zealand orange hoverfly [*Melanostoma fasciatum* (Macquart 1850)]

Syrphidae, drone fly(*Eristalis tenax* Linnaeus 1758)

Calliphoridae, European blue blow fly (*Calliphora vicina* Robineau-Desvoidy, 1830)

Calliphoridae, Australian brown blow fly [*Calliphora stygia* (Fabricius 1794)]

Calliphoridae, European green blow fly [*Lucilia sericata* (Meigen 1826)]

Sarcophagidae, flesh fly [*Oxysarcodexia varia* (Walker 1836)]

Anthomyiidae, seedcorn flies [*Delia platura* (Meigen 1826)]

Stratiomyidae, green soldier fly (*Odontomyia* spp.)

Ephydridae, Ephydrid flies

Bibionidae, March fly [*Dilophus nigrostigma* (Walker 1848)]

Figure 4: Common flies observed visiting seed crops.

2.8 Data collection

Pollinator behaviour was recorded whilst observing the activity of individual insects visiting pak choi and onion flowers during daylight hours (8.45 am – 7.40 pm). Within each field, observations were conducted throughout the day to maximise the distribution of recordings for the key insect species. This was done by alternating the recording of the observed species that were present. Therefore, consecutive recordings of individuals were avoided where possible. However, on occasions, not all pollinating species were observed in the field (either they were not present or present only at certain times of the day). Therefore, recordings conducted throughout a day reflect those species present at the time. To help maximise the spread of species observed over a given time period, up to 15 min was spent after each recording to search for species that had not recently been recorded.

Pollinator activities observed for each individual insect were: 1. contact with stigmas per flower visited, 2. number of flowers visited per inflorescence, 3. time spent on each flower and inflorescence, 4. distance and angle moved by pollinator between inflorescences (2011–12 data only) and 5. hybrid umbel type (male fertile or sterile) within onion fields.

Observational information was recorded directly into an audio digital recorder (Olympus WS-100) and later transcribed and entered into a spreadsheet. For the 2011–12 observations, a second person recorded inflorescences that each pollinator visited during the recording. These were marked by placing a numbered sticky tag around the petiole of each inflorescence once the insect had left the vicinity of the visited inflorescence (i.e. moved greater than an estimated 50 cm from the visited inflorescence). The distance and angle moved between each inflorescence was then measured using a tape measure and a compass.

Wind speed, air temperature, relative humidity and solar radiation (north and south) were also recorded following the recording of behaviour for each insect. Wind speed (km/h) was recorded using Silva Windwatches, temperature (ºC) and relative humidity (%) using Thermo-Hydro recorders and light intensity (watts/m²) (one reading north, and one reading south) using a Daystar meter device angled directly at the sun (N^{th}) and away from the sun (S^{th}). Each measurement was taken at approximate crop height (1.5 m above ground) temperature and humidity were measured in the shade, while all other variables were measured under direct exposure to the sun.

2.9 Data analysis

Initial exploratory statistics showed a high degree of variability in insect abundance and behaviour in relation to all climatic variables measured. Because of this variability, substantial exploratory analysis and graphical modelling of the data is required before it is feasible to carry out appropriate formal statistical analysis of the data or development of a detailed mathematical model to predict the impact of climate change on pollinator behaviour. We assess the influence of climatic variables on mean abundance and behaviour of key pollinators using a range of plots. In these plots, cubic smoothing splines to show the trends in the data from which conclusions on the potential impacts of climate change on crop pollinator activity are drawn. For the pollinator abundance data, the total counts of each insect over all observation points for a field at each observation time were explored. For the analysis we separated observation times into morning evening (6–9 am; 4–8 pm) and mid-day (10 am – 3 pm). This separation was chosen because preliminary exploration of the data revealed some flower visiting species to be more abundant during the morning and evening periods, while others (including our key pollinating species) were most abundant during the mid-day period (see results Figure 5).

The influence of climate on overall crop pollinator diversity was also examined by calculating the total number of individuals present N and Simpson’s 1/D (Magurran 2004):

Simpson’s 1/D:

$$D = \sum_i \left\{n_i \times \left(n_i - 1\right)\right\} \ / \ \left(N \times \left(N - 1\right)\right)$$

Where n_i is the number of individuals present for species i (species that are present).

We chose the Simpson’s index because it provides for an appropriate interpretation. D represents the probability of drawing two individuals randomly from an infinitely large community (Magurran 2004). Thus, 1/D increases from 1 (a single species always drawn) to ∞ (no species drawn a second time).

3 Results

3.1 Overview of Pollinators across five crop species

In total, 78 distinguishable insect flower visiting taxa were observed across the 111 paddocks. Of these, 66 were seen in onion, 60 in pak choi, 43 in carrot, 23 in white clover, and 22 in radish. More taxa were seen on average in carrot crops, with the lowest numbers in radish.

Table 2: Number of distinguishable flower visiting taxa observed, by crop.

Crop	No. fields	Total observed	Per field Min	Max	Med	Mean
Onion	43	66	1	22	10	10.4
Pak choi	40	60	1	24	9	9.5
Carrot	14	43	6	23	14	13.6
White clover	8	23	1	10	7	6.7
Radish	6	22	2	9	5	5.3
Overall	111	78	1	24	10	9.9

Close to 85,000 insects were observed across the 111 fields, with the highest numbers recorded in pak choi (42,113) followed by onion (34,994). On average, the highest numbers per field were seen in pak choi crops, and the least in white clover. The greatest number observed in one field was 982, for a pak choi crop, and the least was just 2 in onion.

Table 3: Summary of individuals observed by crop (over all observation positions and times*).

Crop	No. fields	Total observed	Per field Min	Max	Med	Mean
Onion	43	34994	2	649	133	160.5
Pak choi	40	42113	4	982	172	240.6
Carrot	14	4586	22	305	83	109.2
White clover	8	1289	21	89	56	53.7
Radish	6	1823	17	273	61	101.3
Overall	111	84805	2	982	129	177.8

Numbers of observation positions varied from 2 to 5, and assessment times varied from 3 to 8.

The total number of taxa observed on the flowers of five crop species is listed in Table 4. Honey bees were the most frequently observed overall and also for each of the five crops individually. New Zealand black hoverflies were the second-most observed species overall, followed by Ephydrid flies (Figure 4). New Zealand black hoverflies were observed in good numbers in all five crops, but few Ephydrid flies were observed in carrot or radish crops. The rankings of observed numbers for some species vary noticeably between crops.

Table 4: Numbers observed: top five most abundant species for each crop (ranking), and top 10 species overall.

Taxa	Total	Rank	Onion	Pak choi	Carrot	Radish	White clover
Honey bees (*Apis mellifera* Linnaeus 1758)	41176	1	21157 (1)	17089 (1)	884 (1)	1103 (1)	943 (1)
New Zealand black hoverflies [*Melangyna novaezelandiae* (Macquart 1855)]	5886	2	683 (6)	4086 (3)	579 (2)	503 (2)	35 (4)
Ephydrid flies (Ephydridae)	5759	3	2910 (2)	2811 (4)	6 (33)	0 (-)	32 (5)
March flies [*Dilophus nigrostigma* (Walker 1848)]	5488	4	41 (29)	5307 (2)	0 (-)	140 (3)	0 (-)
Seedcorn flies [*Delia platura* (Meigen 1826)]	3999	5	1657 (3)	2206 (6)	115 (12)	11 (5)	10 (10)
Drone flies (*Eristalis tenax* Linnaeus 1758)	3058	6	284 (14)	2608 (5)	148 (10)	18 (4)	0 (-)
New Zealand orange hoverflies [*Melanostoma fasciatum* (Macquart 1850)]	2527	7	302 (12)	1807 (7)	309 (7)	3 (12)	106 (2)
Flesh flies [*Oxysarcodexia varia* (Walker 1836)]	2157	8	1549 (4)	254 (16)	348 (5)	4 (9.5)	2 (19)
Lasioglossum bees (Smith 1853)	1924	9	1454 (5)	297 (13)	173 (8)	0 (-)	0 (51)
Green soldier flies (*Odontomyia* spp.)	1862	10	422 (8)	1272 (8)	167 (9)	1 (18.5)	0 (-)
Australian brown blow flies* [*Calliphora stygia* (Fabricius 1794)]	892	13.5	260 (16)	262 (15)	370 (4)	0 (-)	0 (-)
European green blow flies [*Lucilia sericata* (Meigen 1826)]	884	15	320 (11)	83 (23)	479 (3)	2 (14)	0 (-)
Ichneumonid wasps (Ichneumonidae)	392	21	290 (13)	42 (27)	9 (25)	0 (-)	51 (3)

*may include a small number of *C. hilli* individuals.

3.2 Pak choi and onion

Further summaries and analyses are restricted to pak choi and onion crops only, given that there were only a small number (<15) of fields observed for the other crops. For these fields, air temperatures over the observation periods ranged from 5.7° to 31.0°, with some variation in the ranges between the regions. Canterbury was the only region where there were fields of both crops.

Table 5: Number of observations (fields) by crop from each region, and summary of air temperatures.

Region	Onion	Pak choi	Total	Temperature		
				mean	min	max
Canterbury	82 (14)	97 (24)	179 (38)	16.7	5.7	30.0
Marlborough	68 (16)	0	68 (16)	21.5	14.0	29.0
Southland	0	37 (9)	37 (9)	12.7	6.0	21.0
Central Otago	35 (5)	0	35 (5)	18.9	8.0	29.0
Wairarapa	33 (8)	0	33 (8)	21.9	10.4	29.5
Auckland	0	22 (4)	22 (4)	15.5	10.4	19.6
Hawke's Bay	0	19 (3)	19 (3)	18.8	13.2	31.0

In addition to restricting to two crops, summaries are also restricted to a subset of flower-visiting taxa. The first ten listed species are considered to be key pollinators (Rader et al. 2009, 2012; Howlett et al., 2011). Seedcorn flies (Figure 4) and Ephydrid flies have been included in this list because they were present in large numbers, and, unlike all other listed taxa, peak abundance for these species was not in the middle of the day, but close to dawn or dusk (Figure 5).

Table 6: Summary of species & species groups explored: Total numbers observed.

Species/ Species group	Importance	Onion	Pak choi	Total
Honey bees	1	21157	17089	38246
Leioproctus bees	2	572	348	920
Lasioglossum bees	2	1454	297	1751
Blow flies†	2	1224	632	1856
NZ black hoverflies	2	683	4086	4769
Drone flies	2	284	2608	2892
Short tongue bumblebees	2	498	916	1414
Green soldier flies	3	422	1272	1694
March flies	3	41	5307	5348
NZ orange hoverflies	4	302	1807	2109
Seedcorn flies	5	1657	2206	3863
Ephydrid flies	5	2910	2811	5721

*. †includes several species from the family Calliphoridae: *C. stygia, C. vicina L. Sericata, C. quadrimaculata, X. Hortona, P. Pseudoredis* and a small numbers of unidentified species.

Of the species explored in detail, honey bees were by far the most frequently observed, followed by Ephydrid flies and March flies (Figure 4). However, abundance varied substantially between the two crops

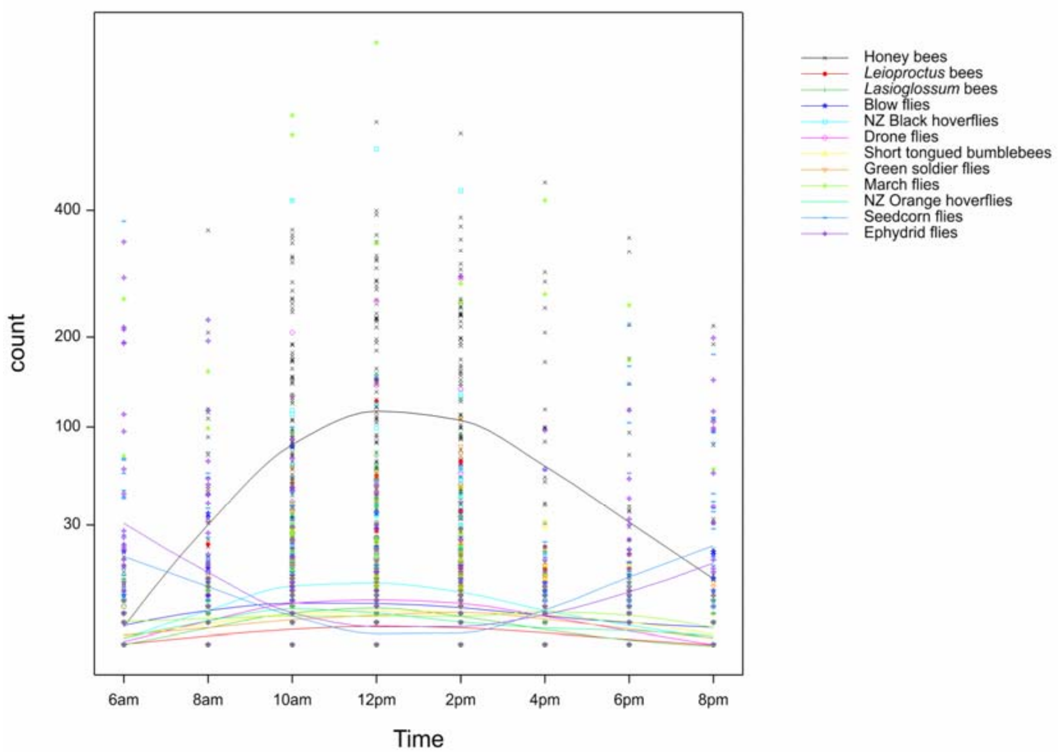

Figure 5: Numbers of counts (points) at each observation time, for selected insects, for pak choi and onion crops only. Trends highlighted with cubic smoothing splines (lines).

3.3 Weather variables

Figure 6 shows the relationship between the important weather variables, as measured from the weather station closest to each field. As might be expected, the temperature variables (air, wet and dew) are quite strongly related. In addition, humidity (RH%) is also quite strongly related to the temperature variables, as is radiation. Thus, it is likely that patterns in insect numbers relating to any of these variables will be similar to each other. Figure 7 shows the relationship between the weather variables and time of day. Obviously, the patterns will vary considerably within individual fields, but there are general patterns that could be useful in identifying pollinator abundance. Temperatures (especially air temperature) and radiation tends to be higher in the middle of the day and relative humidity lowest. Wind also tends to be higher towards the middle of the day. Wind direction appears to have little relationship with time of day. The fields were never located on the coast and therefore catabatic and anabatic wind flows were not likely to greatly influence wind patterns.

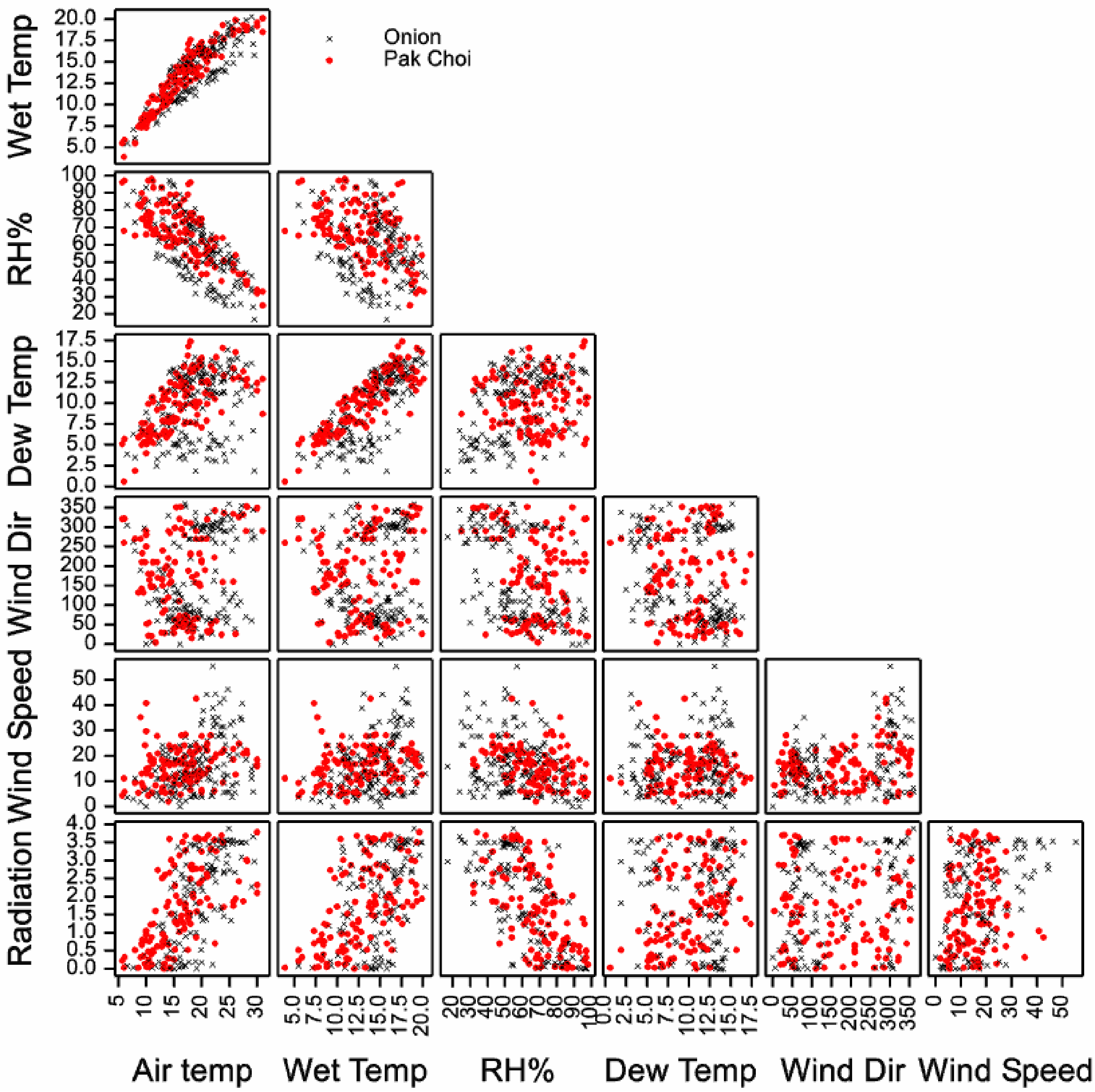

Figure 6: Relationship between the main weather variables, indicating the crop type.

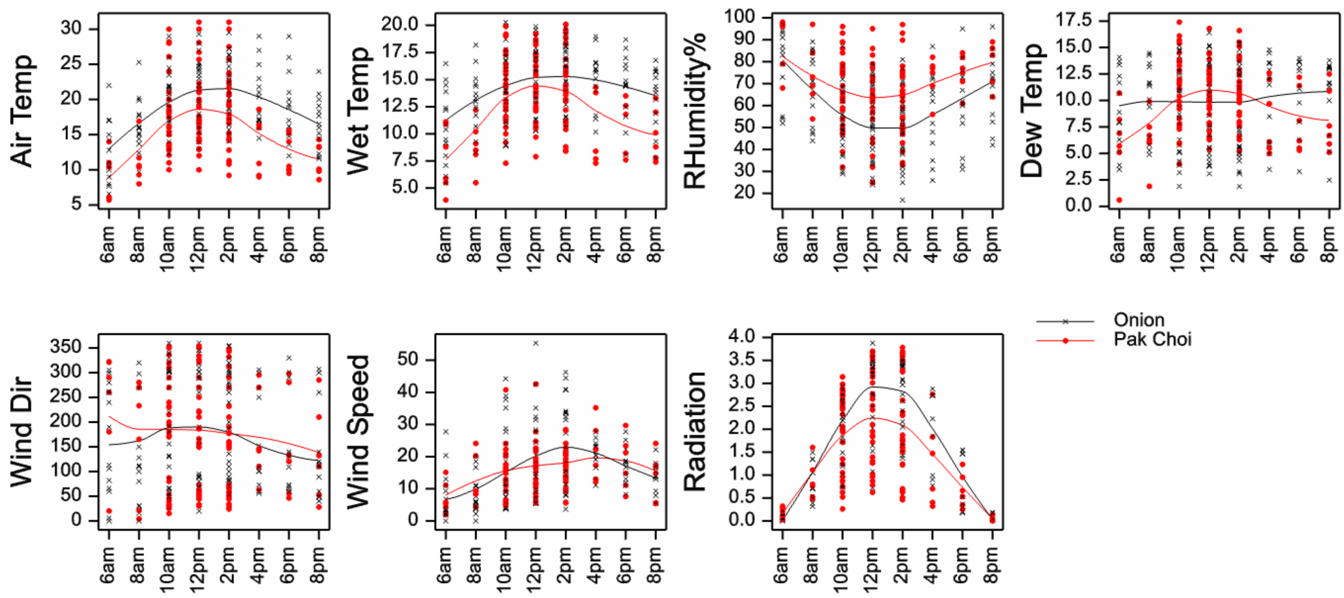

Figure 7: Relationship between each weather variable and time of day, for two crops. Trends are shown with cubic-smoothing splines (lines).

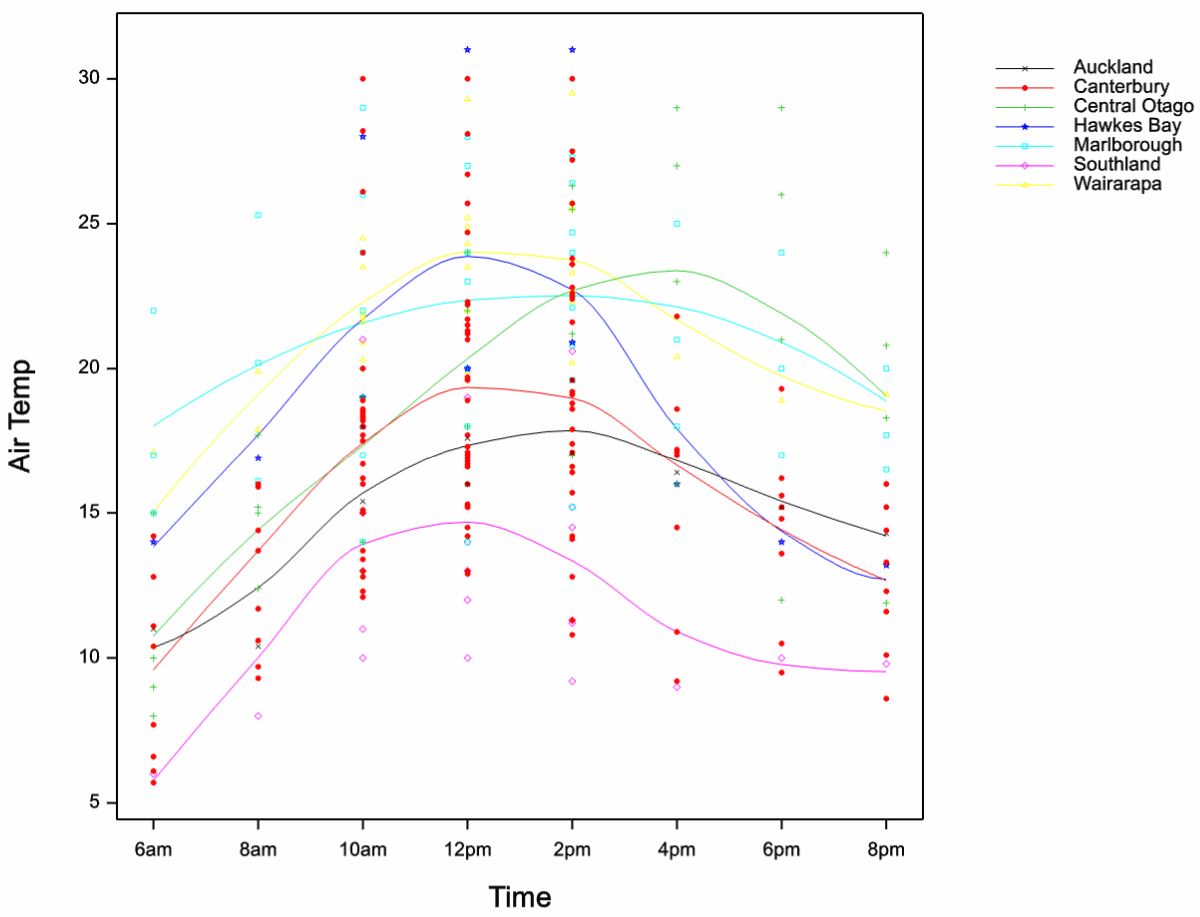

Figure 8: Relationship between air temperature and time of day, by region. Lines show smoothed trends.

3.4 Relationships between flower visitor abundance and weather variables

Figure 9 shows counts of each species in each field at each observation time, with points for the two crops and two sets of times (M/E: morning evening before 10 am and after 4 pm; Midday 10 am to 3 pm) identified. Trends in the counts are approximated by including cubic smoothing splines. The spread of the points at a specific climatic reading demonstrate the variability in the abundance of particular flower-visiting taxa among different fields. There is a tendency for fewer records of taxa counts at the extreme ends of the climatic readings presented in the figures (most observations conducted under average rather than extreme climatic conditions). Therefore, the trends of smoothing splines for each taxa are likely to be of lower accuracy at the more extreme lower and higher readings of each climatic variable.

3.4.1 Temperature

There were some apparent trends in the abundance of different flower visiting taxa within pak choi and onion fields. All key dipteran taxa were present on crop flowers at cool temperatures (below 10ºC) with March flies being particularly abundant (Figure 9). In contrast, the native bees, *Lasioglossum* and *Leioproctus* (Figure 3), were rarely observed at cool temperatures. Honey bees generally appear at temperatures > 9ºC, short tongue bumblebees > 7ºC. Most Dipteran taxa could still be observed at warm temperatures (> 25ºC). However, some were much less abundant than at cooler temperatures (March flies, seedcorn flies). All bee species were most commonly observed on crop flowers at warm temperatures although counts of short tongue bumblebees were higher at cooler temperatures.

Honey bees tended to be most abundant above 24ºC in both pak choi and onion fields, but their abundance differed at lower temperatures depending on the time of day. During the morning-evening period, honey bees were often less abundant than at similar temperatures during mid-day hours (Figure 9). In contrast, the abundance of short tongue bumblebees peaked between 12 and 21ºC and the native bees between 17 and 30ºC. With the exception of March flies, seedcorn flies and Ephydrid flies, which tend to reach peak abundance under cooler conditions, and New Zealand orange hoverflies (peak abundance at 16–20ºC), the abundance of dipteran taxa were widely variable between time of day and crop type.

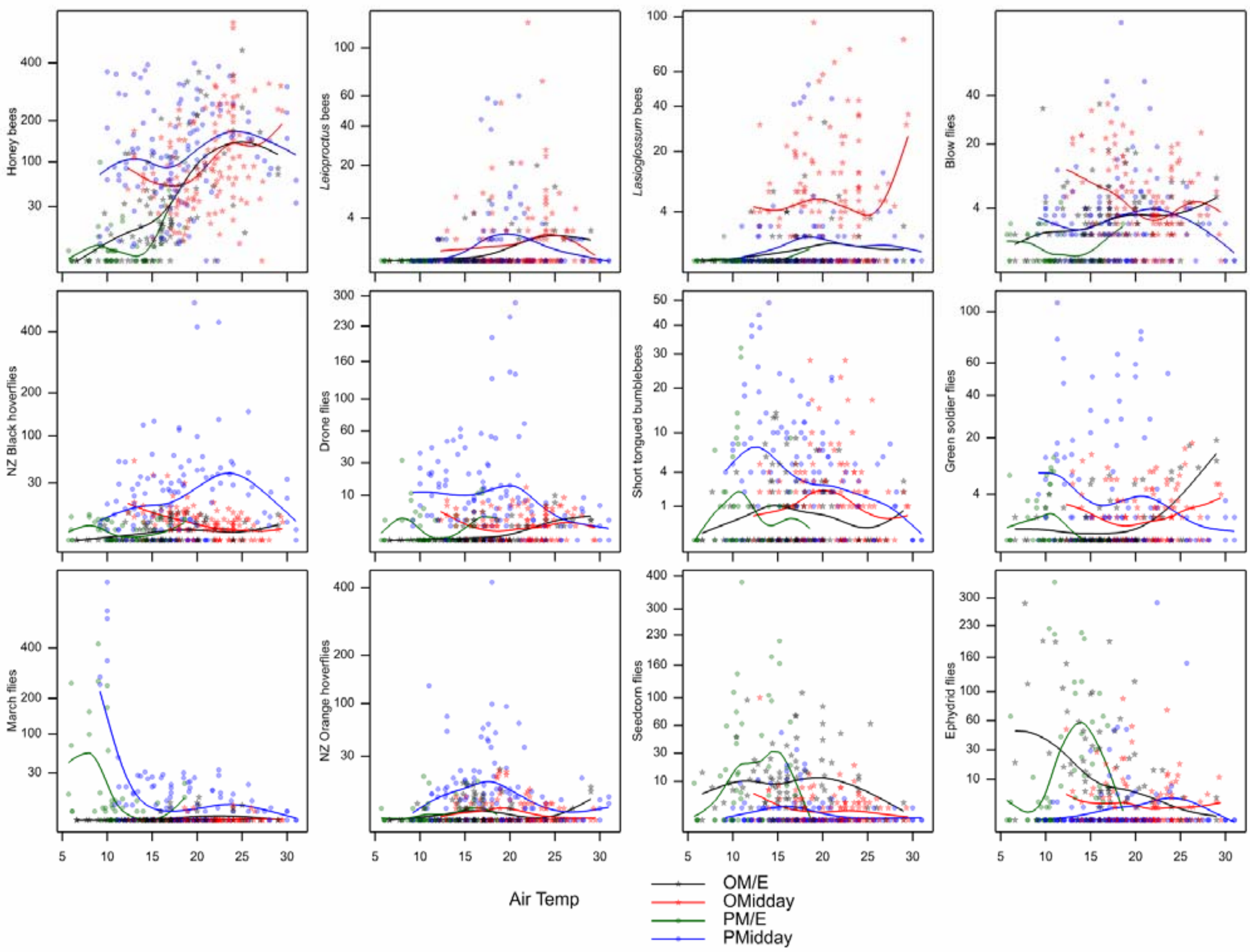

Figure 9: Counts of individuals representing 12 flower-visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields (each point represents one field observation time) versus temperature (ºC). Counts were conducted around mid-day (10 am – 3pm) and morning-evening (M/E: 6–9 am and 4–9 pm. Hourly temperature readings were obtained from meteorological stations within 10 km of field sites. Lines show smoothed trends.

3.4.2 Humidity The abundance of honey bees strongly declined with increasing humidity while there was an opposite trend for short tongued bumblebees (the few data points available for bumblebees in pak choi morning-evening samples are likely to explain the lack of similar trend in the pak choi morning-evening counts) (Figure 10). This trend is opposite to the temperature trends, probably reflecting the negative correlation between temperature and relative humidity.

Unlike honey bees, most fly taxa had relatively low abundances at humidities less than 30%. However, trend lines for green soldier flies were particularly variable, making it difficult to assess any possible correlation. The fly taxa that were more abundant on flowers under cool temperatures (March flies, seedcorn flies and Ephydrid flies) tended to be more abundant when humidity exceeded 50%. The Ephydrid flies during midday observations were an exception, possibly an artefact of the low abundance of these flies at this time. The abundance of orange hoverflies also increased with increasing humidity, as well as a peak in abundance at temperatures 16–20ºC.

3.4.3 Radiation

The abundance of honey bees increased with increasing radiation (Figure 11) with maximum abundance achieved at the highest readings > 2.5 MJ. A relative smaller number of honey bees could also be active under very low light intensity <0.5 MJ, although only during mid-day observations. For other bee taxa (short tongued bumblebees, *Leioproctus* bees and *Lasiolossum* bees) there were no obvious trends between radiation and abundance on flowers, with bees often abundant across a broad range of radiation values.

In contrast to honey bees, most fly taxa (Figure 11) were relatively more abundant at low light intensities (< 2 MJ) than at high light intensities (>2.5 MJ), drone flies were an exception, with a relatively even abundance across the range of light intensities (Figure 11).

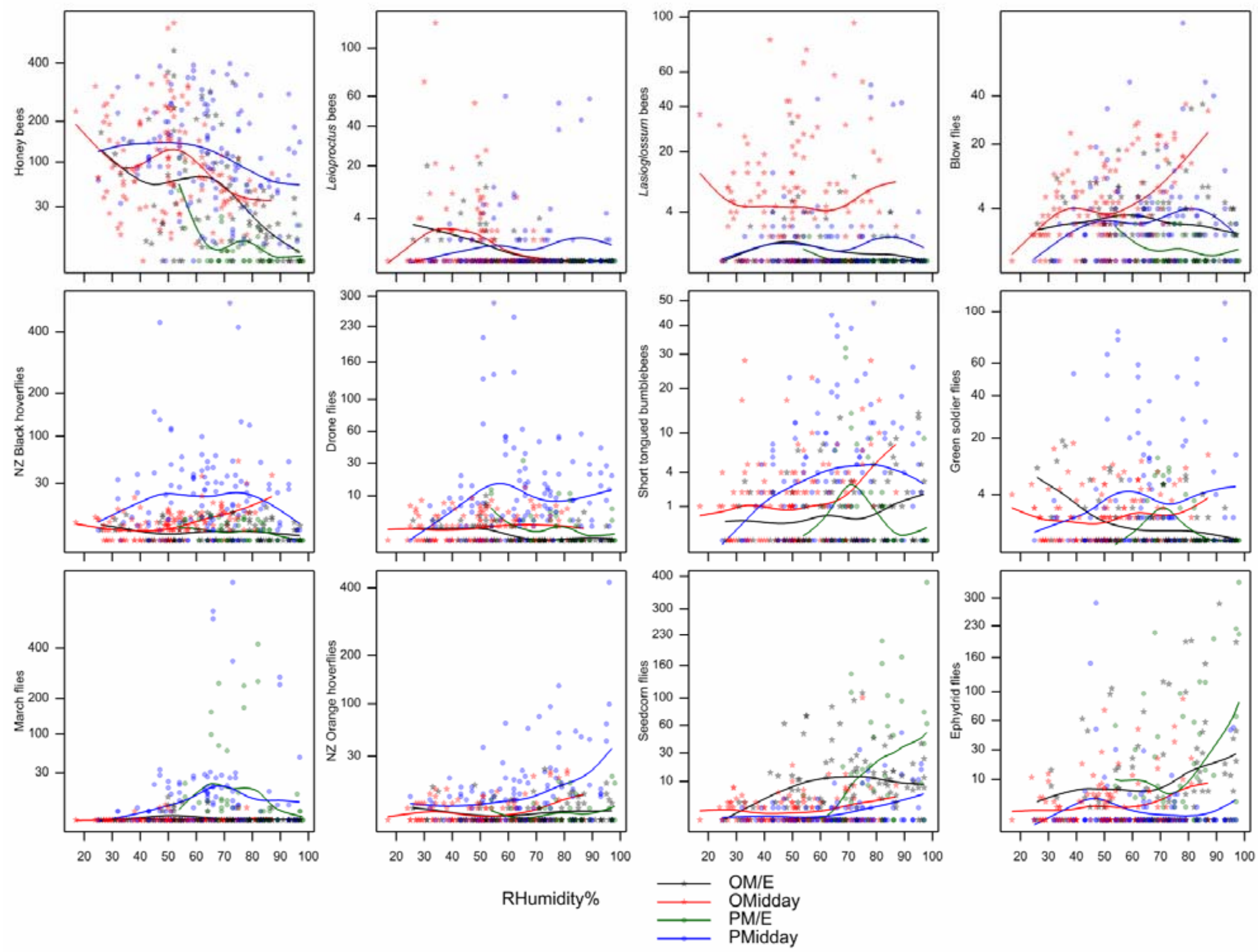

Figure 10: Counts of individuals representing 12 flower-visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields (each point represents one field observation time) versus relative humidity (RH) (%). Counts were conducted around mid-day (10 am – 3 pm) and morning-evening (M/E: 6–9 am and 4–9 pm. Hourly RH readings were obtained from meteorological stations within 10 km of field sites.

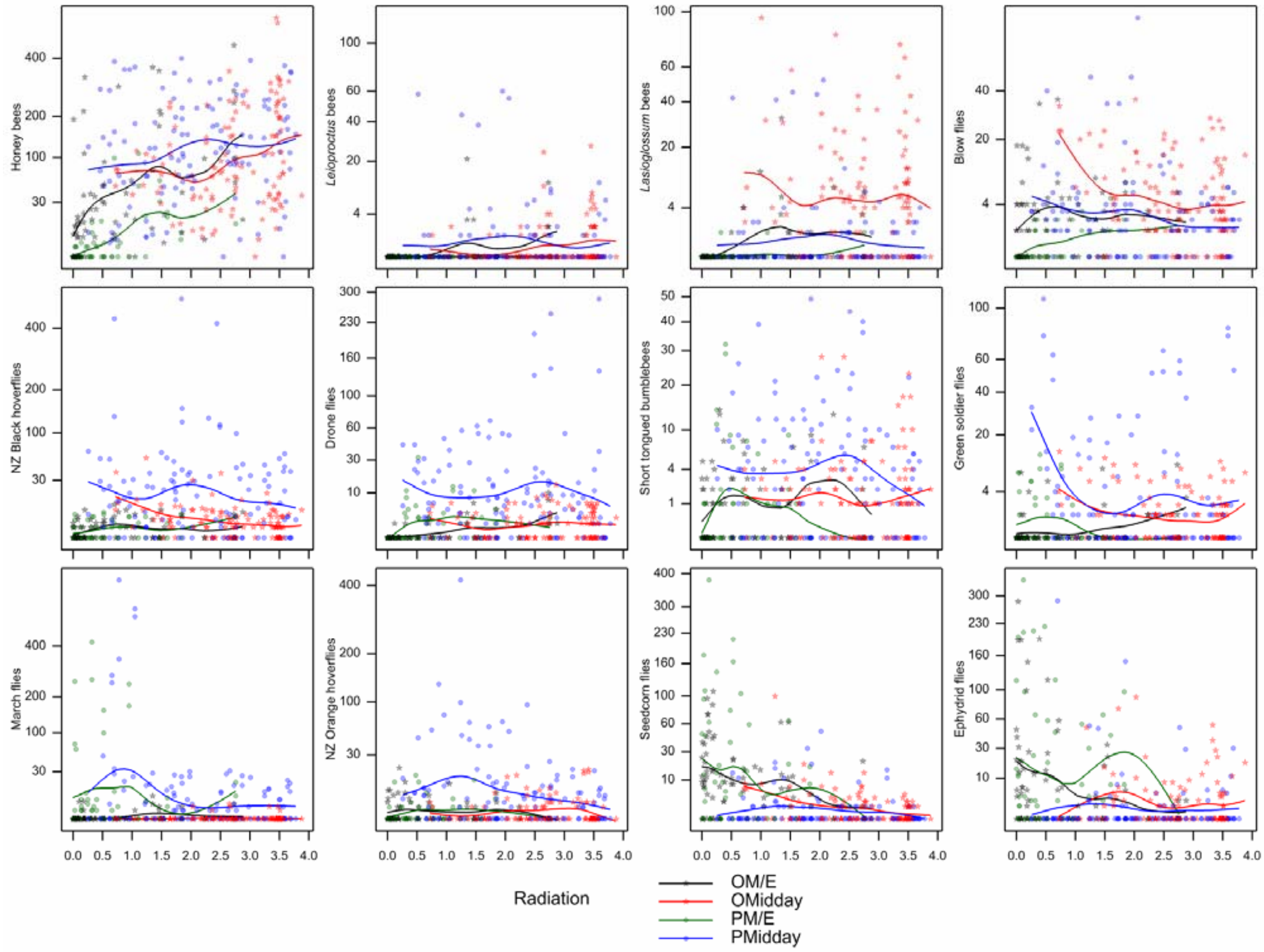

Figure 11: Counts of individuals representing 12 flower visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields (each point represents one field observation time) versus solar radiation (MJ). Counts were conducted around mid-day (10 am – 3pm) and morning-evening (M/E: 6–9 am and 4–9 pm. Hourly solar radiation readings were obtained from meteorological stations within 10 km of field sites.

3.4.4 Wind speed

There was a strong negative trend in relative abundance of honey bees with increasing wind speed (Figure 12). However, the vast majority of observations were conducted at wind speeds of less than 30 km/h. Therefore the trend lines beyond this wind speed become less precise. The relative abundance of *Lasioglossum* bees and New Zealand black and orange hoverflies (Figure 12) showed a decline with increasing wind speed along with those taxa more abundant during morning and evening periods [seedcorn flies and Ephydrid flies (Figure 12)]. There were no clear trends in the abundances of other taxa with activity spread from low to relative high windspeeds (> 30 km/h).

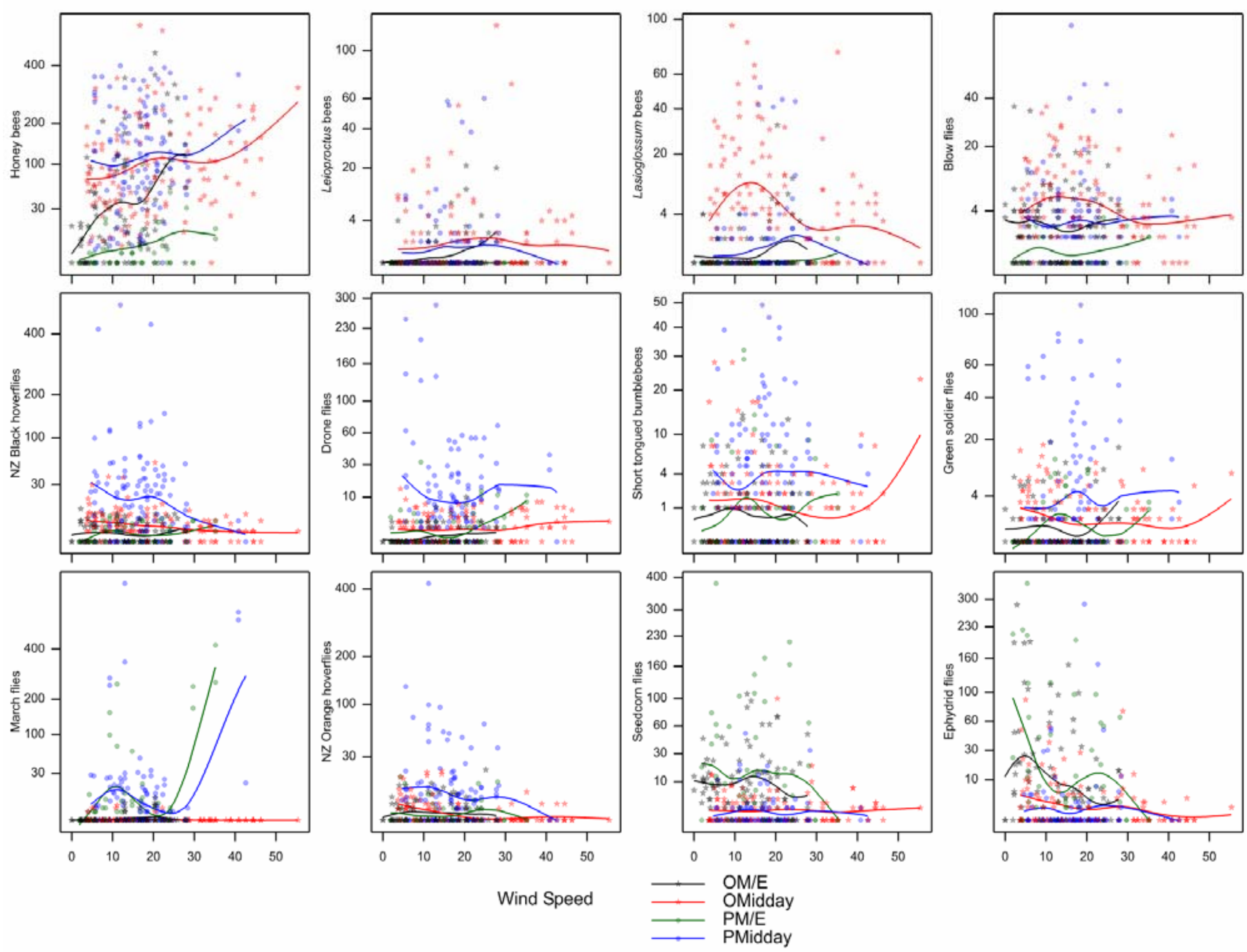

Figure 12: Counts of individuals representing 12 flower-visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields (each point represents one field observation time) versus wind speed (km/h). Counts were conducted around mid-day (10 am – 3 pm) and morning-evening (M/E: 6–9 am and 4–9 pm). Hourly solar radiation readings were obtained from meteorological stations within 10 km of field sites.

3.4.5 Total pollinator abundance

Figure 13 shows total counts of pollinating species observed. The numbers of pollinators on both crops trended to a minimum at an air temperature between 15 and 18˚C regardless of crop. Pollinators on pak choi reached a peak at 22˚C for midday observations, while on onion pollinator counts at midday showed a continuous increase from 17˚C to 30˚C.

Air temperatures for morning-evening observations in pak choi ranged from 5 to 18˚C with little variation in counts with a similar trend for onion over the same range. Counts for onion during the morning-evening increased from 15˚C to a peak of 25˚C.

There was a decreasing trend in pollinator counts for onion for both midday and morning-evening observations as humidity increased. However, for pak choi, counts tend to be fairly similar across the range of humidities measured (Figure 13). Pollinator counts increased when wind speed exceeded 30 km/h (Figure 13) although wind direction (Figure 13) had little effect on counts in either crop. Counts also remained fairly similar across the range of solar radiation measured (Figure 13).

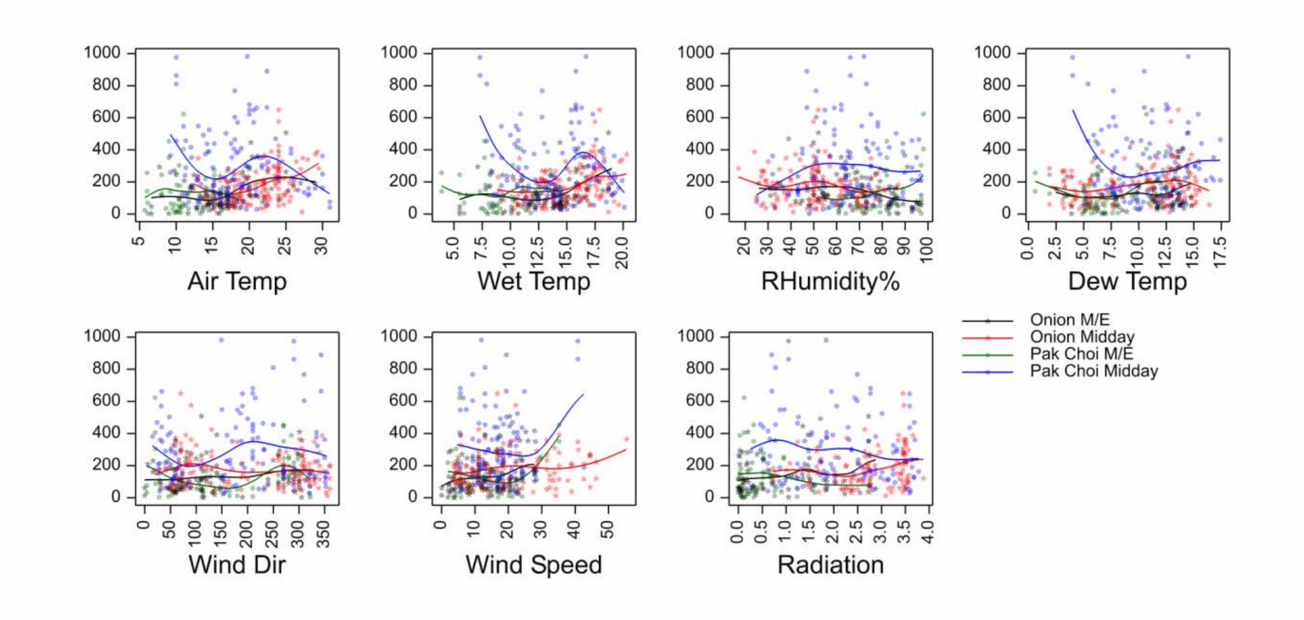

Figure 13: Total combined counts of 12 flower-visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields versus seven climatic variables. Each point represents one field observation. Counts are highlighted for two times of day: mid-day (10 am – 3pm) and morning-evening (M/E: 6–9 am and 4–9 pm). Lines show smoothed trends.

3.4.6 Diversity

Pollinator diversity as measured by the Simpson's Yule 1/D, shows an apparent peak at air temperatures of 15–20˚C (Figure 14), with the reading being almost double the reading at 10˚C and 25˚C. The exception was for pak choi, during the morning-evening observations which had fairly uniform diversity from 5˚C to 17˚C (there were no records of temperatures >17˚C). Within the 15–20˚C range, a number of onion and pak choi fields recorded particular high diversity measures (> 3 times the average).

There was also an increasing trend in pollinator diversity for both crops as relative humidity increased (Figure 14). For both morning-evening and mid-day observations, diversity peaked at between 70 and 100% RH.

Pollinator diversity showed a decreasing trend with increasing wind speed in both crops, although this was only apparent above 30 km/h in pak choi fields observed during the mid-day period (Figure 14). Pollinator diversity also appeared slightly lower when wind came from a westerly direction (270˚) (Figure 14).

Observation under high solar radiation (>2.5 MJ) also recorded reduced pollinator diversity compared with lower radiation (Figure 14). There was a slight peak in diversity at 2.0 MJ for both crops and observation periods.

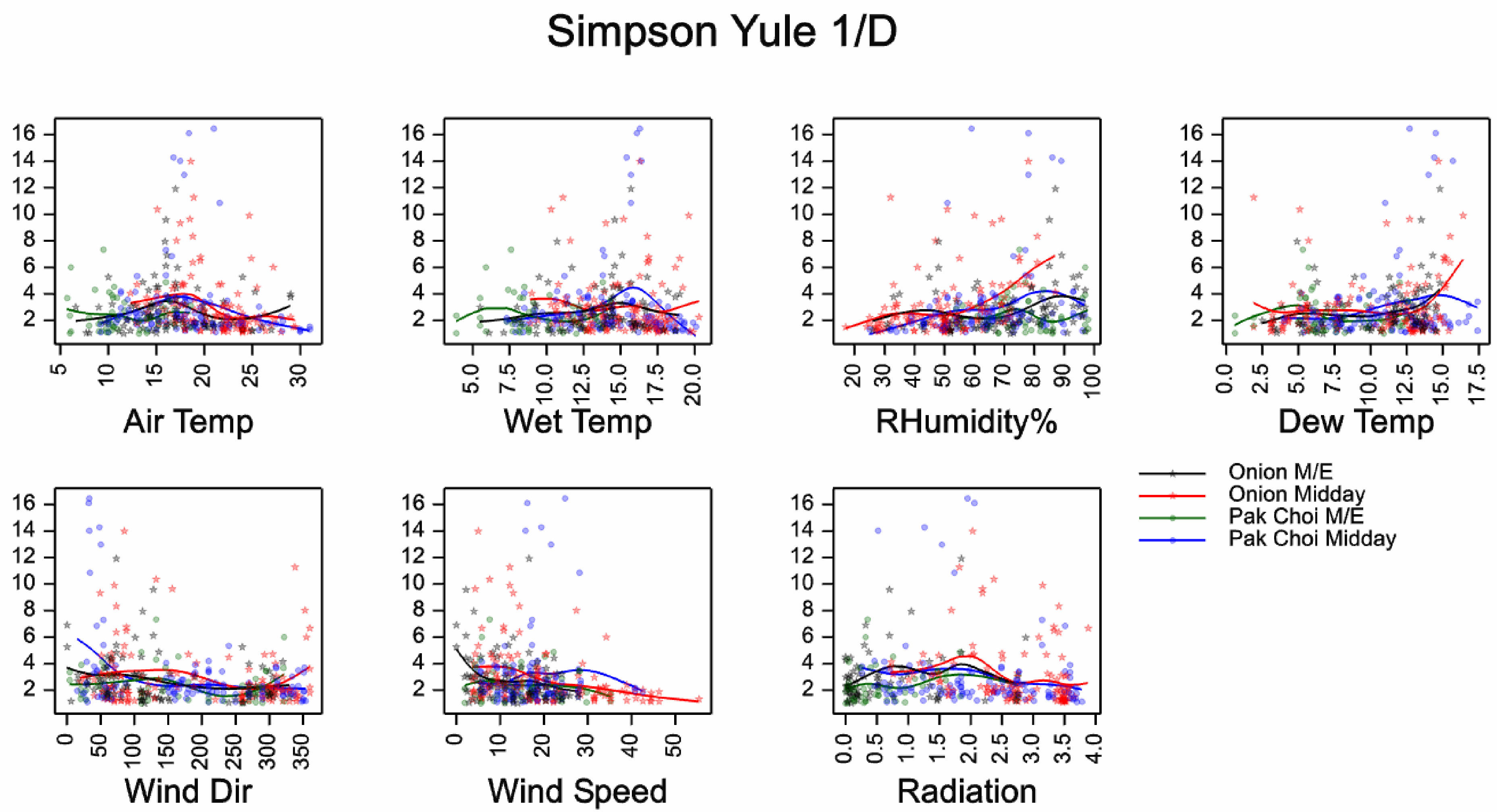

Figure 14: Diversity of flower visiting bee and fly taxa observed in onion (O) and pak choi (P) seed fields as measured by Simpson's Yule 1/D versus seven climatic variables. Each point represents one field observation are highlighted for two times of day: mid-day (10 am – 3pm) and morning-evening (M/E: 6–9 am and 4–9 pm). Lines show smoothed trends.

3.5 Pollinator behaviour

3.5.1 Dataset from the FRST Indigenous Pollinators programme

The majority of data from the FRST programme was collected in December and January of 2005/06 and 2006/07 (Table 7). However, a much smaller set was collected in February and March 2007, and in December 2007. Observations were carried out in both pak choi and onion crops. There was only one month in which both crops were surveyed (Table 7).

Table 7: Number of insects recorded on each month for data obtained in the FRST Indigenous Pollinators programme.

		Jan	Feb	March	Dec
2005	Pak choi	0	0	0	132
	Onion	0	0	0	0
2006	Pak choi	10	0	0	45
	Onion	156	0	0	0
2007	Pak choi	64	27	9	4
	Onion	84	0	0	0

In each region, observations were carried out in 1–4 fields per month (Table 8). Pak choi fields in four regions (Canterbury, Southland, Auckland, Hawke's Bay) were visited, and onion in three (Marlborough, Central Otago, Central Canterbury). No field was visited in more than 1 month per year.

Table 8: Number of fields visited to collect pollinator behaviour data during the FRST Indigenous Pollinators programme. PC = pak choi, O = onion.

	2005		2006		2007		Total		Overall
	PC	O	PC	O	PC	O	PC	O	
Auckland	2	0	0	0	0	0	2	0	2
Hawke's Bay	1	0	0	0	0	0	1	0	1
Marlborough	0	0	0	1	0	4	0	5	0
Central Canterbury	0	0	0	2	0	0	0	2	2
Canterbury	9	0	3	0	4	0	16	0	16
Central Otago	0	0	0	2	0	0	0	2	2
Southland	2	0	4	0	4	0	10	0	10

3.5.2 New data set

Data were collected over 2 months with 555 pollinators observed (December 2011, January 2012)(Table 9). Observations were only conducted in pak choi crops in December 2011, but were conducted in both crops in January 2012.

Table 9: Number of insects recorded on each month for the new data set.

		Jan	Dec
2011	Pak choi	0	150
	Onion	0	0
2012	Pak choi	120	0
	Onion	285	0

In total, five pak choi fields, and four onion fields were visited, across four regions (Table 10). No field was visited in more than 1 month/year.

Table 10: Number of fields visited, in the collection of the new data set. PC = pak choi, O = onion.

	2011		2012		Total		Overall
	PC	O	PC	O	PC	O	
Hawke's Bay	0	0	1	0	1	0	1
Wairarapa	0	0	0	3	0	3	3
Waipara	0	0	0	1	0	1	1
Canterbury	4	0	0	0	4	0	4

3.5.3 Observed taxa

Across both sets, insects of 21 identifiable taxa were observed, comprising 1086 individual insects. All 21 species were observed in the old set, but the new data set focused on eight key taxa as listed in Rader et al. (2009) and Howlett et al. (2011 (Table 11).

Table 11: Number of individuals of each taxa observed in both data sets (old is the FRST Indigenous Pollinators programme data set; new is the new data set).

Insect	Old	New	Insect	Old	New
March flies	21	1	Drone flies	45	88
New Zealand blue blow flies	5	-	NZ blue hoverflies	27	-
Australian brown blow flies	25	41	NZ black hoverflies	45	50
European blue blow flies	20	29	NZ orange hoverflies	41	4
European green blow flies	17	-	Blue Tachinid flies	8	-
Bronze blow flies	14	-	Ginger blister flies	23	-
Blue Muscid flies	9	-	Honey bees	83	191
Spilagona Muscid flies	8	-	Short tongued bumblebees	32	151
Flesh flies	24	-	*Leioproctus fulvescens* bees	7	-
Green soldier flies	29	-	Other *Leioproctus* bees	26	-
			Lasioglossum bees	22	-

The minimum time spent observing an insect was 6 s and the maximum 1688 s (27 min), with means of 245 (4 min) for the FRST programme's data set and 137 (2.3 min) for the new data set (Table 12). Mean temperatures were between 20 and 22°C, but ranged from 15 to 30°C. However, 50% (between q1 and q3, the lower and upper quartiles) of observations were made between 19 and 24°C, a relatively small temperature range (Table 12). Wind speeds tended to be low, below 12 km/ h for the majority (75%) of observations. However, light intensities were more variable (Table 12).

Table 12: Summary of insect observation timed and weather variables (q1, q3: lower and upper quartiles). Old is the FRST Indigenous Pollinators programme data set; new is the new data set.

	Old					New				
	mean	med	q1	q3	range	mean	med	q1	q3	range
Obs.time (s)	244.7	213	137	280	14-1329	137.4	78	43	145	6-1688
Temp. (°)	20.7	21	19	22	13-30	22	22	20	24	15-30
Humid. (%)	46.4	46	38	54	23-71	51.6	52	40	62	24-89
Wind speed (km/h)										
min	1.8	1	0	3	0-20	3.4	2	0	5	0-35
max	6.0	5	2	9	0-30	7.8	6	0	12	0-45
Light intensity										
North	544.5	580	359	716	86-1057	383.2	375	230	510	30-997
South	154.3	138	111	191	50-446	129.1	115	90	154	9-674
Sun	850.2	960	613	1083	136-1347	707.7	780	417	1000	51-1280

3.5.4 Temperature and pollinator behaviour

Of the behavioural variables examined, temperature showed the greatest effect on the number of stigmas visited per minute. For the six fly and bee taxa assessed, the number of stigmas visited per minute showed an increasing trend with increasing temperature (Figure 15).
For the remaining behavioural variables, there were no consistent trends. In onion, drone flies tended to visit more stigmas on inflorescences between 20 and 24°C than at lower and higher temperatures (Figure 15) while for Australian brown blow flies the trend was opposite, with more stigmas visited at temperatures below 20°C and above 24°C.

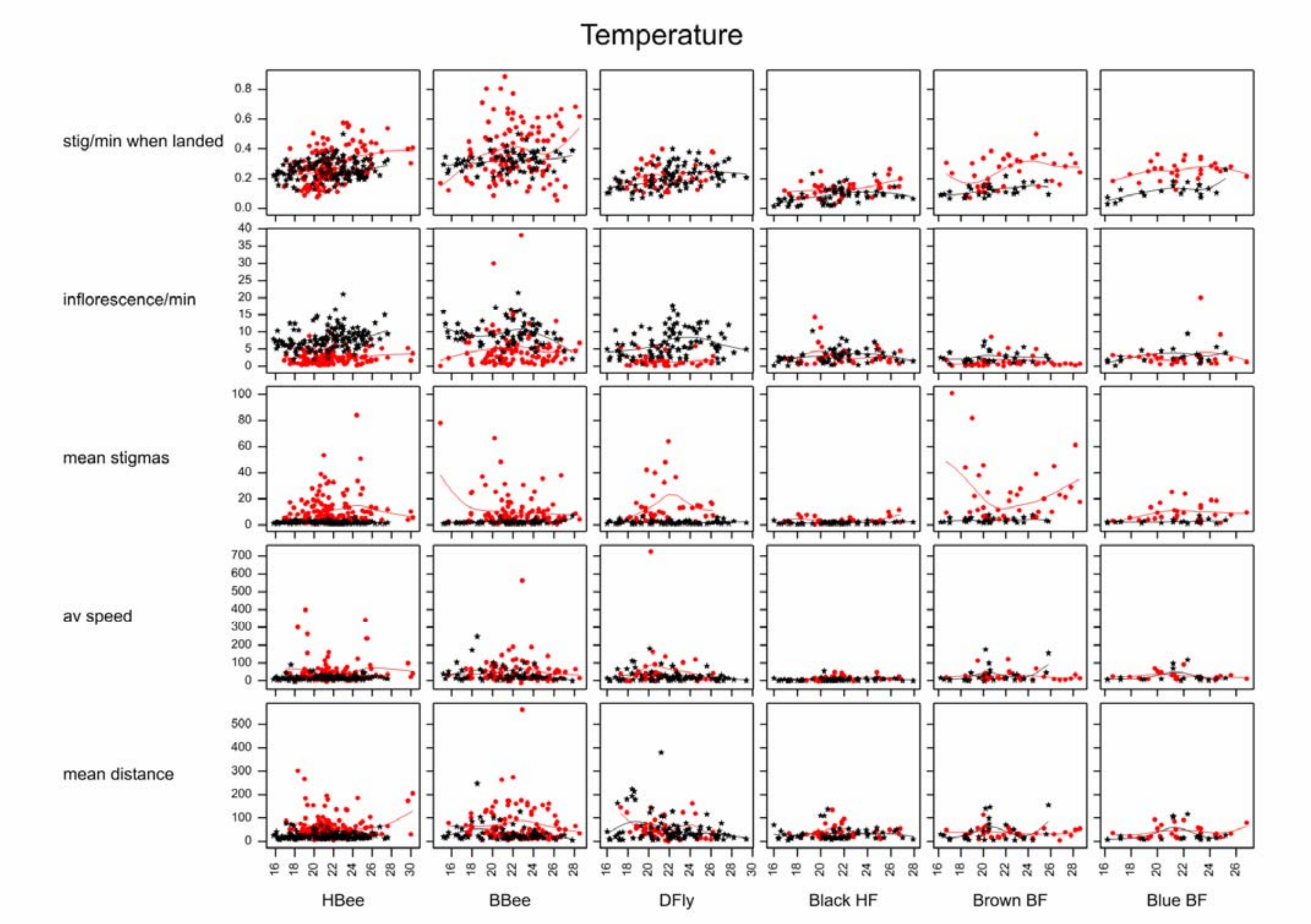

Figure 15: Behaviour of individual flower visiting taxa versus on site air temperature. Behavioural variables measured are: flower stigmas visited per minute when landed, inflorescences visited per minute (includes time to move between inflorescences), mean number of stigmas contacted per inflorescence, average speed of movement and mean distance moved between inflorescences. Each point represents one individual insect. Abbreviated taxa are HBee: honey bees, BBee: short tongued bumblebees, DFly: drone flies, Black HF: New Zealand black hoverflies, Brown BF: Australian brown blow flies and Blue BF: European blue blowflies. Lines show smoothed trends.

3.5.5 Other climatic variables and pollinator behaviour

Relative humidity, light intensity, and mean wind speed were also examined. However, variation in these climatic variables did not correspond with any clear trends in the behaviour variables (e.g. Figure 16) of the different bee and fly pollinator taxa. An exception may be honey bees and bumblebees that may visit fewer stigmas per minute as humidity increases, but the relative flatness of the trend between RH 40 and 70% at which foraging individuals were mostly recorded makes drawing a conclusion to trends tenuous (Figure 16).

Figures for the other climate variables versus pollinator behaviour are presented in Appendix 2.

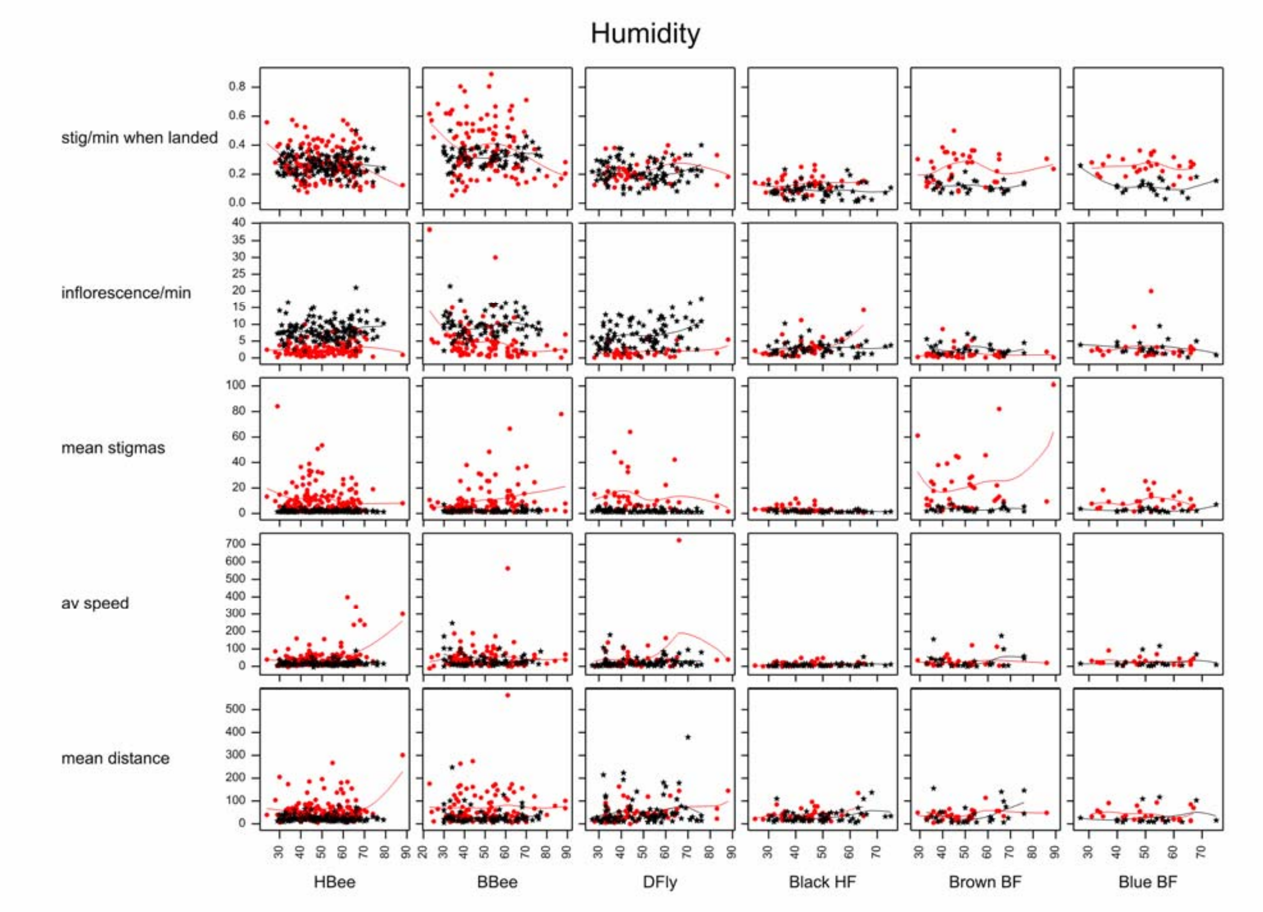

Figure 16: Behaviour of individual flower visiting taxa versus relative humidity (%). Behavioural variables measured are: flower stigmas visited per minute when landed, inflorescences visited per minute (includes time to move between inflorescences), mean number of stigmas contacted per inflorescence, average speed of movement and mean distance moved between inflorescences. Each point represents one individual insect. Abbreviated taxa are HBee: honey bees, BBee: short tongued bumblebees, DFly: drone flies, Black HF: New Zealand black hoverflies, Brown BF: Australian brown blow flies and Blue BF: European blue blowflies. Lines show smoothed trends.

4 Discussion

4.1 Pollinators of New Zealand seed crops

The most abundant flower-visiting insect taxa observed in this report are widespread in New Zealand crops (Howlett et al. 2005, 2009; Rader et al. 2011, 2012) and have been previously reported visiting crops from a variety of plant families including pak choi (Brassicaceae), onion (Amaryllidaceae) (Howlett et al. 2009) and kiwifruit (Actinidiaceae) (Macfarlane & Ferguson 1984). The most common and widespread are flies [drone flies, New Zealand black hoverflies, New Zealand orange hoverflies (Syrphidae) Australian brown blow flies, European blue blow flies (Calliphoridae); March flies (Bibionidae); seedcorn flies (Anthomyiidae); and Ephydrid flies (Ephydridae)] and bees [(honey bees, short tongued bumblebees (Apidae); native *Leioproctus* bees and *Lasioglossum* bees (Halictidae)]. This study has demonstrated that most of these insect taxa are key flower visitors for a wider range of crops such as carrot (Apiaceae), radish (Brassicaceae) and white clover (Fabaceae). They are also common flower visitors in native ecosystems (Donovan 2007; Heine 1937; Newstrom & Robertson 2005; Primack 1983). Many of these insects have also been specifically identified as key pollinators of pak choi (Howlett et al. 2011; Rader et al. 2009, 2012) and kiwifruit (Macfarlane & Ferguson 1984). Given their widespread occurrence, abundance and likely importance as pollinators for crops across New Zealand, they have been the focus of this study.

4.2 Pollinator abundance and time of day

The time of day had a noticeable effect on the abundance of some flower visiting taxa. Honey bees and the syrphid flies (black hoverflies and drone flies) were most abundant at mid-day from 10–3 pm, blow flies (total of all Calliphoridae) and March flies were commonly observed throughout the day (6 am – 9 pm) while seedcorn flies and Ephydrid flies were much more abundant during morning and evening times (6 am – 9 am and 4 pm – 9 pm) than at mid-day. The factors influencing changing diurnal presence on the flowers of crops are different for each insect taxa and may be influenced by a number of factors (e.g. the quality of nectar and pollen available, predation, radiation). In this study, we separated our analysis of insect abundance into morning-evening observations and midday observation because of the distinct differences among abundances of some insect taxa with these times of day. It was also noted that in the case of honey bees, the similarity of climatic variables between morning-evening and mid-day observations did not necessarily correspond with abundances (e.g. lower temperatures, solar radiation, wind speeds and higher humidity). This difference was not explored but may possibly be due to the influence of interactions between multiple climatic variables, or due to the possible requirement by foraging honey bees to perform different tasks within the hive.

4.3 Pollinator abundance and climate

The abundance of flower-visiting insect taxa to onion and pak choi seed crops varied with respect to climate variables as measured from meteorological stations within 10 km of field sites. Owing to the relationships between several climatic variables it is difficult to assess the degree to which a specific climate variable influences pollinator abundance despite there being some clear trends in the abundance of specific insect taxa in relation to specific climate variables.

Occasionally where there was a changing trend in the abundance of an insect taxon corresponding with variation in a specific climate variable, similar trends were observed in related climate variables. For example, honey bees that were more abundant at high temperatures (25°C) than at low temperatures (<20°C), also showed increasing abundance with increasing light intensity and decreasing humidity.

The trends of increasing honey bee abundance with increasing temperature, solar radiation, and decreasing humidity is compatible with research that details the constraints of honey bee flight in relation to low ambient temperature (i.e. honey bees maintain thorax temperatures >30 °C for flight). However, honey bee workers are particularly adept at foraging in high ambient temperatures, being capable of continuous flight at temperatures up to 46°C. At high temperatures honey bees maintain a cooler thorax temperature by transferring heat through the head and regurgitated nectar (Heinrich 1993). They are also capable of gaining some heat through the absorption of solar radiation whilst on flowers to assist with body temperature maintenance (Heinrich 1993; Kovac & Stabentheiner 2011). However, solar radiation absorption is a minor component of maintaining or building warmth compared with many Diptera (Heinrich 1993).

There was also an increasing trend in the relative abundance of honey bees with increasing wind speed. To our knowledge, previous research has not directly associated the abundance of foraging honey bees with increasing wind speed. Therefore, this trend may reflect those days where observations were conducted in the presence of relatively strong north-westerly winds. Apart from strong, gusty winds, these conditions typically consist of warm air temperatures (often exceeding 30°C), relatively low humidity and medium to high solar radiation (variables that match with higher honey bee abundance). Therefore, these variables represent a particular pattern of climatic events rather than just windspeed.

In contrast to honey bees, the relative abundance of short tongued bumblebees on crop flowers showed an opposite trend with respect to the same climate variables. Bumblebee species are commonly found throughout temperate regions and even above the arctic circle, with some species capable of regulating thoracic temperatures above 35°C (suitable for flight) at air temperatures near 0°C (Heinrich 1993). However, due to their large body mass and mechanisms that are less efficient at keeping cool than honey bees, bumblebees are more restricted in their ability to forage at high temperatures (Heinrich 1993; Peat et al. 2005).

The two native bee taxa, *Leioproctus* and *Lasioglossum*, are smaller than honey bees in size and, therefore, like honey bees may be constrained in their ability to fly in cooler temperatures. Foraging by these bees was commonly observed at temperatures above 12°C and remained abundant at temperatures above 25°C. There have been no studies examining the thermoregulation of New Zealand native bees and therefore mechanisms to control body and thorax temperatures are unknown. However, these bees are predominantly dark in colour, thus suggesting an ability to absorb solar radiation under cool climatic conditions as predicted by the thermal melanism hypothesis (Clusella-Trullas et al. 2008). *Lasioglossum* bees have also been observed sitting on flowers on sunny winter days in New Zealand (Donovan 2007) and may therefore gain heat through the absorption of solar radiation to assist with flight.

A range of dipteran taxa including blow flies, hoverflies and soldier flies was found to be relatively abundant across a broad range of temperatures (from < 15°C to 30°C), humidity (particularly from 30 to 80%) and solar radiation (particularly from 0.5 MJ to 3.5 MJ). The occurrence of these flies across a broad range of climate variability supports findings that many Diptera have greater flexibility to forage under a wide range of climates, particularly cooler and moister conditions than honey bees (Gonzalez et al. 2009; Heinrich 1993; Kearns

1992). However, for those Diptera that were more active during the morning-evening periods (6am – 9 am, 4 pm – 9 pm), relative abundances were more associated with climatic variables typical for these periods such as lower temperatures and lower solar radiation (and lower light intensity). Increasing wind speed also corresponded with decreasing abundances of the smaller fly taxa (seedcorn flies, Ephydrid flies and New Zealand orange hoverflies).

The relative abundance of March flies in pak choi fields appear to be particularly high under colder temperatures, high humidity, high wind speed and low solar radiation relative to other taxa. These findings more likely reflect the limitations of the analysis than represent a true pattern of relative abundance. March flies were very abundant in pak choi fields in Southland compared with other regions and observations were conducted on days where temperatures did not exceed 13°C. In other fields where March flies were present in lower numbers, other flies could be observed foraging at temperatures greater than 25°C. March flies were also particularly abundant during December observations (pak choi only) and were rarely observed in January-flowering pak choi and onion.

4.4 Pollinator diversity, total pollinator abundance and climate

Pollinator diversity as measured by the Simpson's Yule 1/D did not correspond closely with total pollinator abundance. Diversity peaked below 20°C, while peak abundance occurred above 20°C. Diversity also tended to be greater at higher relative humidities and at lower solar radiation and wind speed. In contrast, total abundance tended to increase with increasing wind speed, while there were no clear trends with respect to relative humidity or solar radiation.

The different patterns between the two measures may be largely explained by changes in the evenness aspect of the diversity measure. Although the abundance of some Dipteran taxa declines with increasing temperature and related climatic variables, other Diptera remain present at temperatures approaching 30°C. However, the greater abundance of honey bees (one of the most abundant taxa) at higher temperatures increases the unevenness of the diversity measure, therefore reducing diversity. For pak choi, both pollinator abundance and diversity declined at temperatures greater than 25°C. If this trend is accurate then high temperatures may have a negative impact by reducing pollinator abundance and diversity. A similar trend was not observed in onion fields where pollinator abundance continued to increase at high temperatures. The differences in these trend lines may be the result of a number of factors. These include fewer observations conducted at high temperatures, which may have reduced the accuracy of the trend lines, or alternatively, different foraging strategies by pollinators on crops. For example, brassicas are attractive forage plants to honey bees whereas onions are less attractive (Free 1993). Therefore, honey bees placed in onion fields may forage on alternative preferred plants that may be present in the environment (e.g. crops and weeds). The abundance of other preferred plant species can therefore influence the abundance of honey bees within the targeted fields. However, if honey bees exhaust the alternative resources (e.g. nectar and/or pollen), then they may choose to forage on the less preferred crop species leading to increased abundance within the crop (Free 1993) irrespective of direct climatic influences.

4.5 Pollinator behaviour and climate

Despite climate variability being linked to changes in the behaviour of pollinators, just one of the behavioural variables we tested showed a trend with changing climate. In this case, all bee (honey bees, short tongued bumblebees), and Diptera (drone flies, New Zealand black hoverflies, Australian brown blow flies and European blue blow flies) taxa showed a tendency to visit more stigmas per minute with increasing temperature. These findings therefore suggest that the efficiency of pollinators to transfer pollen between flowers within inflorescences may be increased if the ability to transfer pollen remains the same. Therefore, crops that can be self-pollinated but benefit from insect pollination (e.g. some brassica species) (Free 1993) could receive increased rates of pollen transfer per insect. However, most insect pollinated crops grown in New Zealand require or benefit significantly from cross-pollination (Cunningham et al. 2002). Those variables we tested that are likely to influence pollen transfer between plants by insects (inflorescences visited per minute, mean stigmas visited per inflorescence, average speed and mean distance moved) did not show any consistent pattern with regard to climate variability.

4.6 Crop pollination and climate change

This study predicts that the activity of some insect pollinators of crops in New Zealand will be altered under current climate change forecasts published by Ministry for the Environment (2008). The relative abundance of key fly and bee crop pollinating species (Macfarlane & Ferguson 1984; Rader et al. 2009, 2012) observed over 89 flowering onion and pak choi fields located throughout South and North Islands of New Zealand, differed with respect to variation in temperature, humidity, solar radiation and wind speed as recorded from meteorological stations located within 10 km of field sites. These climatic variables are most likely to affect the abundance of specific insect pollinating taxa, and only affect pollinator behaviour with respect to the number of stigmas pollinators contact per minute within an inflorescence (a variable that is only likely to enhance self-pollination).

In New Zealand, predictions for climate change up to year 2100 are highly variable among regions (Mullan et al. 2008). Therefore, the impact of climate change on pollinator assemblage diversity on crops is likely to vary widely across New Zealand. Table 13 lists important New Zealand grown crops that benefit from insect pollination to maximise crop yield (Free 1993; Cunningham et al. 2002; Klein et al. 2007).It also lists the regions in which they are predominantly grown. We use this table to discuss how pollinator assemblages are likely to be altered within these regions due to climate change. Although climate change may lead to changes in production across New Zealand dependent on climate suitability we focus on the impact of climate change on crop pollinator assemblages.

Table 13: Major insect pollinated crops by area (total area planted > 1000 ha) grown in New Zealand. Major growing regions for each crop are also listed [Statistics New Zealand 2007 except [1]Fresh Facts 2011 (2007 data)].

Crop	Region (area ha)	Total area ha
Vegetable seeds	Canterbury (5537)	7330
Kiwifruit	Bay of Plenty (10,249)[1]	13,250[1]
Pome fruit *(Apples. Pears, Nashi)*	Hawke's Bay (5 408) Tasman (2722)	10,038
Stone fruit *(Peaches, Apricots, Cherries, Plums)*	Hawke's Bay (895) Otago (941)	2258
Blackcurrants	Tasman (453) Canterbury (660)	1155
Citrus *(Orange, Grapefruit, Lemon, Manderin, Tangelo)*	Gisborne (1 003)	1834
Avocados	Bay of Plenty (2210) Northland (1325)	4004
Squash	Hawke's Bay (3117)[1] Gisborne (2773)[1]	7774[1]
Peas and Beans	Canterbury (5242)[1] Hawke's Bay (1062)[1]	7515[1]

4.6.1 Canterbury

Canterbury is currently a major region for the production of vegetable and other seed crops [including carrot, radish, turnip, chinese brassicas (such as pak choi), rape, kale, onion, white clover)] as well as blackcurrants. Stone fruit, pome fruit, and raspberries are also grown on a moderate scale (each > 50 ha) (Statistics New Zealand 2007). In this region key climatic variables that are predicted to have the biggest change over the next century are temperature (increase by 0.7–5.0°C), days where maximum temperature exceeds 25°C (20–45 days) and decreased rainfall (0–5%), the number of drought days on the plains expected to double (Mullan et al. 2008). These changes are likely to see increased foraging activity by honey bees over the crop flowering period associated with increased bee abundance and longer foraging times (suitable foraging conditions are likely to extend within and between days). However, some pollinators are expected to be negatively affected. Optimal foraging conditions for short tongued bumblebees are expected to decrease due to increasing periods of diurnal temperatures > 25°C. Some fly species are likely to be impacted as well, e.g. orange hoverflies. However, there may be limited impact on other species such as *Leioproctus* and *Lasioglossum* bees, blow flies, green soldier flies and drone flies that were relatively abundant on crops over a broad range of climatic conditions. Overall, with temperatures exceeding 25°C for longer periods of time during the seasons that these crops are grown, pollinator diversity is expected to decrease as honey bee abundance increases with respect to other pollinating species.

4.6.2 Tasman

A variety of insect pollinated crops are grown in the Tasman region. Along with major crops listed in Table 13, Boysenberries and raspberries are also important crops with planted area >50 ha (Statistics New Zealand 2007). In this region key climatic variables that are predicted to have the biggest change over the next century are temperature (increase by 0.6–5.0°C), days where maximum temperature exceeds 25°C (30–45 days) and a slight increase in rainfall (2.5–5%) (Mullan et al. 2008). However by 2090, there is likely to be twice as many very heavy rainfall events and an increase in the number of storms compared to the number in 1990. As with Canterbury, increasing temperatures are likely to lead to an increase in honey bee foraging abundance, although the increasing number of storms and heavy rainfall events could increasingly interrupt foraging. The impact on non-honey bee pollinators is likely to be variable. Bumblebee foraging periods may be reduced with increasing temperatures, however, they are likely to forage more readily than honey bees during periods of higher rainfall and storms. Some of the dipteran pollinators that forage across a broad range of climatic conditions (e.g. blow flies, drone flies and soldier flies) may also be more resilient than honey bees under these unstable climatic conditions

4.6.3 Hawke's Bay and Gisborne

Along with crops listed in Table 13, insect pollinated crops covering >50 ha in Hawke's Bay are kiwifruit, stone fruit and vegetable seeds, while in Gisborne they are pome fruit, kiwifruit, avocado and persimmon (Statistics New Zealand 2007). In these regions temperature is expected to increase by 0.6–5.5°C; by 2100, there may be 30–50 extra days where maximum temperature exceeds 25°C while there is predicted to be quite marked seasonal changes in rainfall with winter-spring decreases of more than 7.5% and summer-autumn increases of 2.5–9% (Mullan et al. 2008). The number of heavy rainfall events and summer storms is also expected to increase (Mullan et al. 2008). Longer periods of warm temperatures during the flowering period of crops are likely to see increased honey bee activity; however, increasing rainfall and storms, could have some impact on foraging times of honey bees and other pollinators (Blaschon et al. 1999; Gonzalez et al. 2009). Likewise, changes in rainfall and associated humidity may lead to an increasingly fly-dominated assemblage (Devoto et al. 2005). The Ministry for the Environment (2008) indicates that there is high variability between models with respect to rainfall predictions; therefore, it is difficult to assess the likely impact of this variable on crop pollination. As described for Canterbury, warmer temperatures are likely to reduce the activity time of short tongued bumblebees and some fly species.

4.6.4 Bay of Plenty

Along with crops listed in Table 13, insect pollinated crops covering >50 ha are feijoas and vegetable seeds (Statistics New Zealand 2007). In this region temperature is expected to increase by 0.6–5.5°C by 2100, there may also be 30–65 extra days where maximum temperature exceeds 25°C while rainfall is expected to decrease in spring (estimated 9%) but remain close to the current average in the other seasons (Mullan et al. 2008). Despite annual rainfall not expected to increase significantly, heavy rainfall events and the number of summer storms (decreased intensity) are expected to increase (Mullan et al. 2008). Increased temperatures and fine weather should favour honey bee foraging, however, during periods of unstable weather (e.g storms) pollinators that show greater flexibility in their foraging under variable climatic conditions (e.g. some dipteran species) will be key pollinators.

4.6.5 Northland

In addition to the crops listed in Table 13, insect pollinated crops covering >50 ha are kiwifruit, citrus and macadamia (Statistics New Zealand 2007). Northland's temperature is expected to increase by 0.6–5.9°C by 2100; there may also be 45–70+ extra days where maximum temperature exceeds 25°C while rainfall is expected to remain similar to the current average during summer and autumn but decrease in winter and spring (estimated 8–16%) (Mullan et al. 2008). Heavy rainfall events and the number of summer storms (decreased intensity) are expected to increase (Mullan et al. 2008). The influence of these conditions on pollinator activity is likely to show a similar but more extreme trend than Canterbury. This reflects the greater proportion of days per year where maximum temperatures exceed 25°C. Therefore, higher temperatures are likely to enhance honey bee pollinator activity as opposed to short tongued bumblebees and those diptera more abundant under cooler temperatures and result in lower pollinator diversity, particularly for summer pollinated crops. However, pollinators capable of foraging under wide climatic conditions will be favoured over honey bees during periods of stormy weather.

4.6.6 Otago

In addition to stone fruit, insect pollinated crops covering >50 ha are vegetable seeds and pome fruit (Statistics New Zealand 2007). Otago's temperature is expected to increase by 0.8–4.6°C by 2100. There may also be 10–45 extra days where the maximum temperature exceeds 25°C while rainfall is expected to remain similar to the current average during summer and autumn but increase in winter and spring (6–7% in Dunedin; 15–29% in Queenstown) (Mullan et al. 2008). As with many other regions in New Zealand, heavy rainfall events and the number of summer storms (decreased intensity) are expected to increase (Mullan et al. 2008). Because climate change is expected to have less effect on temperature compared to the rest of New Zealand, the impact on pollinator activity should also be less. However, if higher rainfall during the spring (flowering period of stone fruit) translates to increased hours of rainfall then the pollinator activity, particularly of honey bees, is likely to be reduced (Gonzalez et al. 2009). Under these conditions, and with a predicted increase in the number of summer storms, maintaining pollinator diversity should be an important goal for maximising crop pollination.

4.7 Limitations of the study

The current study strongly suggests that climate affects the relative abundance of different pollinating taxa differently. It also points to climate having a relationship with pollinator behaviour in terms of stigmas contacted per minute. Abundance and behaviour trends for particular insect taxa were often similar for both crop species, suggesting that climate affects pollinator activity. Differences in relative abundance between the insect taxa observed are also supported by knowledge of bee and fly thermodynamics (Heinrich 1993) and studies examining the composition of pollinator assemblages in locations that differ in climatic conditions (Gonzalez et al. 2009; Heinrich 1993; Kearns 1992). However, a number of factors could have influenced trends for particular taxa observed or led to an increase in the variability of the data.

In general, taxa were widespread and common across fields throughout New Zealand. However, the occurrence of individual taxa is likely to be influenced by the ecology of the insect, particularly factors influencing lifecycle, population dynamics and landscape factors (Tscharntke & Brandl 2004; Tscharntke et al. 2005). These factors may have significant influences on the abundance of specific pollinating species between and within fields in New Zealand (Howlett et al. 2005). For example, competing bloom from nearby crops can particularly have a significant impact on pollinator abundance within a specific crop (Dag et al. 2005; Ellis & Delaplane 2009). In this report, the data presented for March flies demonstrates how localised but highly abundant populations (i.e. very high observation counts in Southland fields that were observed only under cold temperatures < 13°C) can potentially distort the relationship between climate and abundance.

Another limitation of the study was that for the pollinator abundance data, information on climate corresponding to the times of observation was collected from offsite meteorological stations. These were located within 10 km of field sites with recordings taken at hourly intervals. Therefore the analysis was unable to consider site-specific climate at the exact time of observation. Microclimate can have a significant influence on pollinator activity by altering local site factors (Torres-Diaz et al. 2007) and climate surrounding the plant itself (Heinrich 1993; Herrera 1995) and therefore may have contributed to the large variability in abundance counts within specific climatic ranges.

For the behaviour data, climatic variables relating to each observed pollinator were measured within the field and directly after each recording. Therefore, this data provides a more direct linkage between pollinator behaviour. However, non-climatic factors may have influenced the behaviour of pollinators. These include timing of nectar and pollen production within crops, which in particular can show large variation in the production and composition of nectar with respect to cultivar (Ali et al. 1984). Variation in the behaviour of individual pollinators from within the same taxa (e.g. through age, experience) (Durisko et al. 2011) may have occurred within and between sites increasing the variability of the data.

4.8 Climate change and pollinator-crop interactions: Future Research

This study has presented information on how key climatic variables affect the abundance and behaviour of key insect pollinators found in some New Zealand crops. It predicts that the abundance of particular pollinators and the diversity of pollinator assemblages will change as climate warms. However, crop pollination and production will also depend on factors that were not studied in this report. These include:

1. Climate change on pollinator lifecycles and subsequent population dynamics. For example, the larval development rate of different Dipteran species can be altered significantly but not consistently under different climatic regimes leading to variation in lifecycle completion (Niederegger et al. 2010). Moreover, the season range of some species may be altered, e.g. *Lasioglossum* bees can be present on flowers on warm winter days (Donovan 2007).

2. Climate change on crop cultivation. The production of crops within and between regions is likely to change. Changing conditions may suit the development of new cropping industries. However, it may become unsustainable to grow certain crops within their current regions. For example some brassicas currently grown in Canterbury require vernalisation over winter to enhance spring flowering. The predicted reduction of frost days up to 2100 (Mullan et al. 2008) (i.e.milder overnight temperatures) may lead to inadequate vernalisation therefore restricting the future planting of these crops in Canterbury.

5 Conclusion

Insect pollinators work seed crops in a very wide diversity of climatic conditions. This study confirms earlier observations that there is a stable core group of species providing effective pollination on these annual crops, regardless of North or South Island geographic ranges. However pollinator activity windows were found to differ with changing climate (specifically a 4^{o}C increase in temperature, but also humidity, light intensity and wind). This alters pollinator abundance, diversity and behaviour, with different pollinating taxa having variable responses to climatic variables.

Honey bees are currently the single most abundant species on these crops and temperatures >25^{o}C tend to result in an even greater dominance of honey bee abundance, relative to other pollinators. These findings indicate that increasing temperatures per se should not impact on their pollination performance but may enhance it, if adequate numbers remain available. The availability of honey bees for crop pollination is dependent on successful management strategies to control varroa mite and related bee health issues as well as competing industries (e.g manuka).

However, climate change forecasts predict an increased frequency of extreme weather events such as drought and flood that could impact honey bee pollination. In these circumstances, honey bee pollination of crops, particularly those that flower for a short period (e.g pak choi 2-3 weeks) is at greater risk. Strategies that build pollinator diversity, particularly for species that pollinate under climatic conditions less suitable for honey bee foraging, should help safeguard crop pollination services.

The observation that abundance of most insect pollinators occurs through the middle hours of the day is not surprising. The projected shift to an increase in proportion of days above 25^{o}C for most regions suggests a decrease in current effectiveness of some of these unmanaged insects (e.g. short tongued bumblebees, New Zealand orange hoverflies) as a pollination service to these crops. However, a number of key fly species were shown to be active over a broad range of climate (e.g. drone flies, blow flies) and their foraging on crops is less likely to be influenced by climate change.

Floral constancy is a feature of many insects, including honey bees. The higher value of F_1 hybrid seed crops suggest that these will continue to be a major focus for the seed industry and therefore inefficiency of pollination services in these crops will continue to be a focus of concern. We need to change pollination research emphasis towards both resolving the floral constancy problem and retaining a focus on species with potential to remain abundant into future climate scenarios.

Climate change scenarios suggest that, assuming the same or highly similar crops are still grown, the current stable but diverse range of insect species providing pollination services might shift in species composition somewhat, but this is more likely to occur at a diurnal level. Earlier research efforts have already identified the need to emphasize insects less inclined to floral constancy and this requirement will be exacerbated, especially as a temperature shift upwards tends to favour honey bees.

6 Acknowledgements

We thank Smith Seeds Ltd and associated farmers who provided seed for a pak choi trial and allowed access to pak choi crops. Seminis Vegetable Seeds NZ Ltd, South Pacific Seeds (NZ) Ltd and associated farmers for access to onion crops. Samantha Read, Heather McBrydie, Samantha Rowland (Plant & Food Research), Maxime Musso, Charles Rollet (Agrocampus Ouest) for assisting with field work. Nick Pyke and staff from the Foundation for Arable Research for useful discussions and assistance with field work. This project was funded by SLMACC C11X1101.

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APPENDIX 1 Projects which provided data towards this report

FRST C02X0221 THE ROLE OF INDIGENOUS POLLINATORS AS NEW ZEALAND SPECIFIC MECHANISMS FOR TRANSGENE FLOW

Specific mechanisms for transgene flow

The purpose of this programme is to identify New Zealand-specific pathways, especially by indigenous pollinators, for pollen dispersal within and between productive and natural environments, in order to better understand the potential environmental impacts of genetic modification and support the development of risk assessment models to predict the risk of pollen-mediated transgene escapes. Progress towards achieving the programme outcome remains excellent with research into pollen dispersal revealing findings of considerable interest to the research community and stakeholders.

Research into three key factors influencing pollen dispersal (flower visitor assemblage composition, pollinator effectiveness and pollinator movement) has been groundbreaking and has demonstrated that:

- flower visitor assemblages of important seed crops are very diverse and the abundance, distribution and diversity of key pollinators is highly variable between fields and regions (e.g. Howlett et. al., 2005, NZ Plant Protection 213-216);
- many indigenous and introduced bee and fly species are effective pollinators of commercial brassica and onion crops; and
- many of the key pollinators are vectors of viable crop pollen and are constantly moving from crops into the surrounding landscape. Further, our research has revealed that night flying insects play only a minor part in Brassica and onion pollination, while for onion small insects (less than 3 mm wide) do not appear to contribute significantly to pollination.

These findings are both nationally and internationally important because they have identified the potential significance of many indigenous and introduced species as vectors of crop pollen. We have also demonstrated the potential limitation of overseas many GM risk assessment models for gene flow that do not consider the full potential of insect vectors. Our research is providing fundamental understanding of the insect communities involved in crop pollination that will assist the development of risk assessment models that more accurately predict the risk of unwanted environmental pollution through gene escape via insect mediated pollen movement.

The key end users of our research findings are ERMA, MfE, DoC and MAF. Strong links have been maintained with these agencies through annual meetings with discussion focussing on the information they need to refine the policy development process. They view the findings valuable for risk assessment of GM crop introductions (evaluating proposals for GM trials, assessing the potential impact of unintentionally introduced GM products) and for understanding biodiversity contained within NZ agro-ecosystems. The programme's industry support group, which features South Pacific Seeds (NZ) Ltd, Smith Seeds Ltd, Seminis Vegetable Seeds NZ (Ltd), PGG Wrightson Ltd, continues to grow with the inclusion this year of Kiwi Seed Company Ltd. In-kind support from these companies has ensured that a wide range of commercial fields across New Zealand have been available for research purposes, ensuring our research findings are of national relevance.

New national and international linkages have also been established with several research organisations, which have strengthened the research in this programme through the establishment of joint projects and partnerships. Three students (2 PhD and 1 Masters) are linked to the FRST programme with heads of agreement established with, James Cook University (QLD), CSIRO Australia and Canterbury University (Christchurch). Scholarship funding has been provided by James Cook University and the Department of Australian Agriculture, Fisheries and Forestry. Partnerships that are facilitating the exchange of information and greater understanding of current advances in research fields have been established with Guelph University (Canada) and Griffith University (Australia).

SFF 05/122 CODE OF PRACTICE FOR MANAGING POLLINATION OF VEGETABLE SEED CROPS

The project aims to develop a Code of Practice for protecting vegetable seed crops from cross-pollination. It will include the current SCID system to manage crop planting isolation distances and will also provide recommendations for beehive management.
This project has given the industry some guidelines for the use of the electronic seed crop isolation distance programme. It has brought the seed industry together to discuss this important topic on a regular basis. The project has lead to a greater understanding of how each company works and allowed for greater cooperation between companies on this important topic. The code of practice has put some guidelines on paper for the individual companies to work towards and strengthened the working relationships built during the original SCID project.

Activities carried out during this project have highlighted the fact that for New Zealand to remain an attractive area for seed production, guarantees of seed quality are required, of which seed crop isolation is a key area. Having an electronic isolation distance programme gives New Zealand a large advantage over other areas in the world where pin boards are still being used.

SFF 07/035 SUSTAINABLE POLLINATION OF SEED CROPS IN THE PRESENCE OF VARROA; WHERE TO FROM HERE?

The problem has arisen from the presence of Varroa destructor. The infection of honey bee (*Apis mellifera*) hives with varroa in the South Island will have a significant effect on the availability of honey bees to pollinate arable seed crops. It is therefore essential that the arable seed industry develops a sustainable plan for pollinating these high value crops for when varroa becomes widespread, to ensure the local and export production needs (approx $60 million) continue to be met. The establishment of the varroa mite in the North Island of New Zealand in 2000 has led to a decrease in honey bee hive numbers and the importation of extra hives from the South Island. With the recent discovery of varroa in the South Island, and a decision by government to manage rather than eradicate the mite, the expense of using honey bees as seed crop pollinators is expected to increase significantly. This is due to a decline in hive numbers and the ongoing costs of varroa management. For insect pollinated crops, the western honey bee is almost solely relied upon to conduct pollination services in New Zealand. The cost of hiring hives by industries relying solely on the honey bee for pollination services is expected to increase significantly (estimated $40 per hive, MAF 2003). Varroa mite is an external parasite of adult and developing stages of honey bees. Infested colonies are weakened by the decline in the number of adult honey bees while emerging bees may be less active (MAF 2003). Varroa mite is expected to cost South Island agriculture $314 million by 2035. Annual impacts on arable industries are likely to be $1.57 million (MAF 2003).

Urgent action is required to ameliorate the predicted loss of revenue caused by the spread of varroa and to ensure continued sustainability of industries that are currently reliant on honey bees for pollination. To address this we propose the following initiatives:

- Accurately estimating the required numbers of bees/ha for specific crops in New Zealand to ensure pollination services are provided at optimal levels. Currently many estimates of the number of honey bees required are purely based on farmer and company representative experience, compared to scientifically proven data.
- In some seed crops, unmanaged pollinators have been found to be contributing significantly to pollination services (up to 50%) (Howlett unpublished). Identifying environmental features and landscape factors that influence the occurrence and abundance of unmanaged but efficient pollinating species, such as the introduced bees *Bombus spp*., native bees *Leioproctus* and the larger flies from the families *Syrphidae, Calliphoridae* and *Bibionidae*, will ensure their services as pollinators are better harnessed. Tools will also be developed to predict their spatial and temporal abundance along with methods to increase their abundance.

This project will provide an understanding of both managed and unmanaged pollinators in an effort to sustain the current level of pollination in a rapidly growing industry.

A major benefit of having these type of projects is that at least once a year all the vegetable seed producing companies meet in one room to discuss the issues they have with pollination. It is also a forum for them to hear what the scientists think is happening in some of their fields. These views are often different and any chance to discuss why is seen as valuable from both sides. This project has changed the thinking of the people involved away from only looking at honey bees as a source of pollination to thinking about flies and other insects also. Another major change in thinking has been around the thinking of bee stocking rates i.e. number of foraging bees, not the number of hives/ha.
This has meant that we are now willing to incorporate other insects into our pollination plan, not just honey bees

APPENDIX 2 Pollinator Behaviour and climate variability

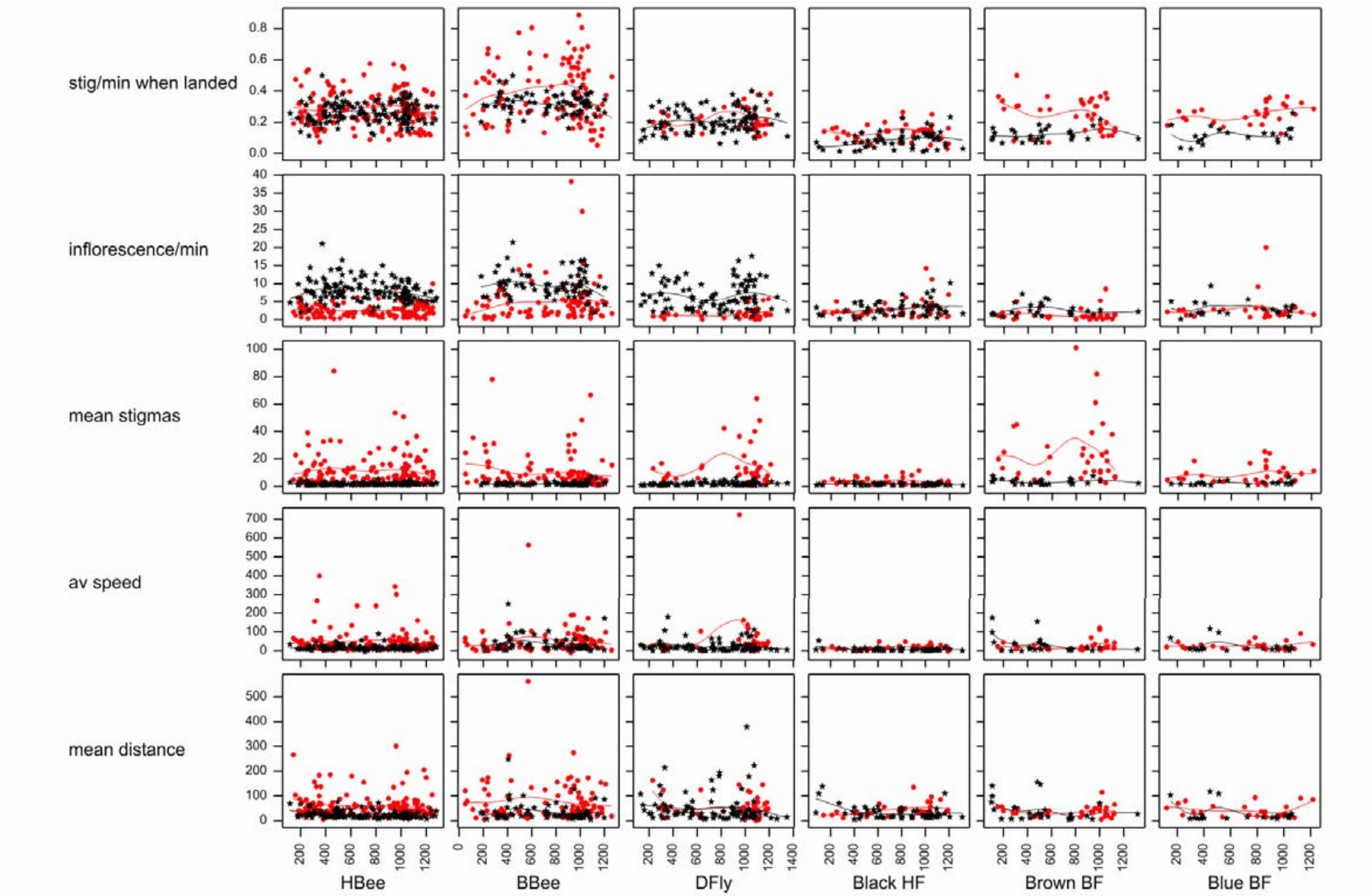


Figure A1: Behaviour of individual flower visiting taxa versus relative light Intensity (w/m2) (surface of device directed towards sun). Behavioural variables measured are: flower stigmas visited per minute when landed, inflorescences visited per minute (includes time to move between inflorescences), mean number of stigmas contacted per inflorescence, average speed of movement and mean distance moved between inflorescences.

Each point represents one individual insect. Abbreviated taxa are HBee: Honey bees, BBee: Short Tongued Bumblebees, DFly: Drone flies, Black HF: New Zealand Black Hoverflies, Brown BF: Australian Brown Blow flies and Blue BF: European Blue Blow flies.

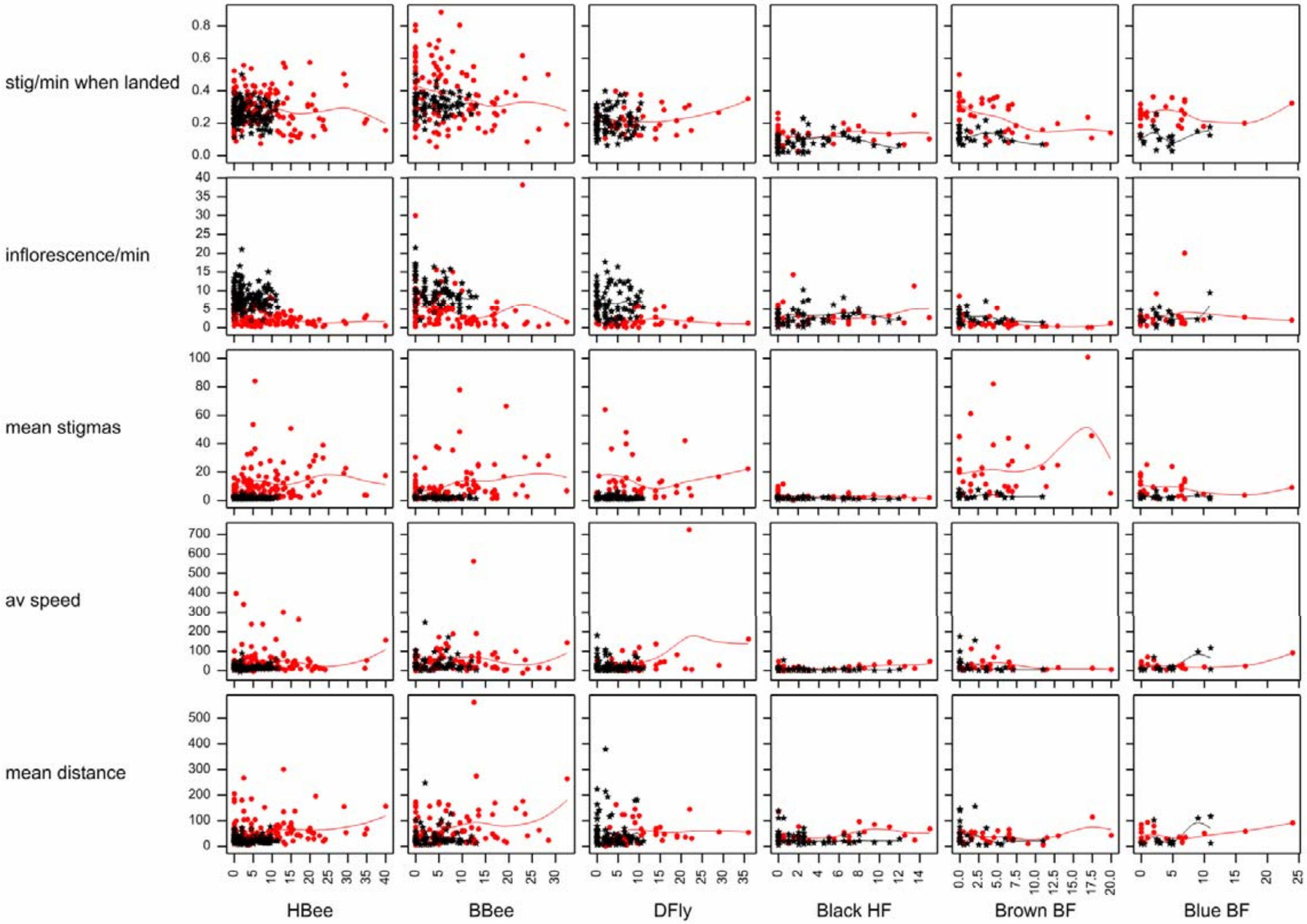
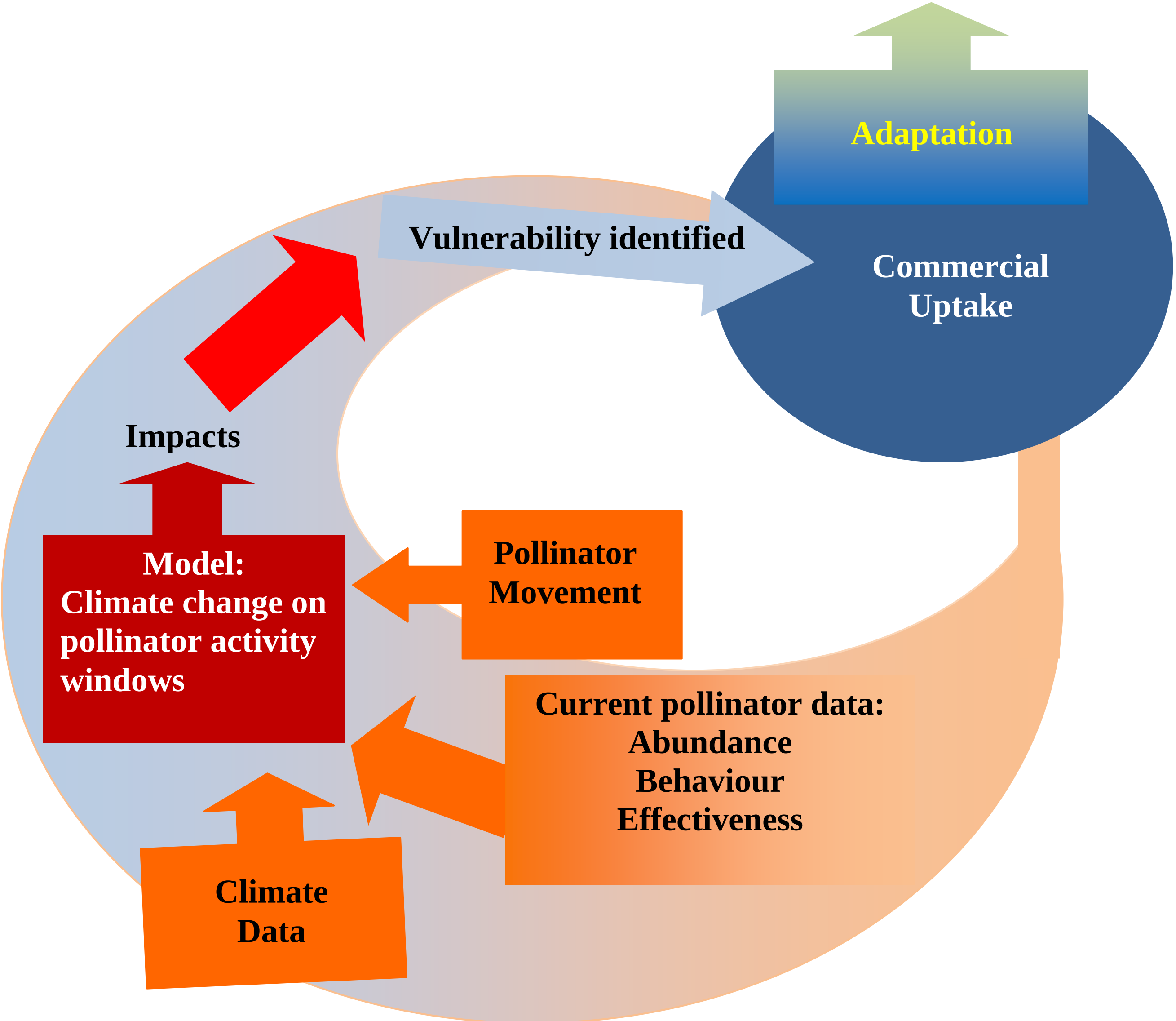


Figure A2: Behaviour of individual flower visiting taxa versus mean windspeed (km/hr) (measured over a 20 second period). Behavioural variables measured are: flower stigmas visited per minute when landed, inflorescences visited per minute (includes time to move between inflorescences), mean number of stigmas contacted per inflorescence, average speed of movement and mean distance moved between inflorescences. Each point represents one individual insect. Abbreviated taxa are HBee: Honey bees, BBee: Short Tongued Bumblebees, DFly: Drone flies, Black HF: New Zealand Black Hoverflies, Brown BF: Australian Brown Blow flies and Blue BF: European Blue Blow flies.

APPENDIX 3: Project Plan, Current and Future Outputs

Impact of climate change on crop pollinator activity windows

Project Plan:



Aim: Assess pollinator activity windows and the influence of climate change.
Benefit to New Zealand will be improved and adaptable seed industry
Targets SLMACC theme priority 3.1
Critical Step 1 – synthesis of climate change effects
Critical Step 2 – industry workshop
Critical Step 3 – report to industry on Impact, Vulnerability, Adaptation strategy
Critical Step 4 – submitted paper for peer reviewed publication
Critical Step 5 – final report including indicative industry impacts

Synthesis of climate change effects

Data was drawn from:

- Two pre-existing data sets detailing pollinator abundance and behaviour (recordings taken under widely varying climatic variables) (FRST Indigenous Pollinators Programme, FRST C02X0221). This data was collected from commercial hybrid onion crops and commercial/non-commercial non-hybrid pak choi crops.

- A specifically designed study to assess the influence of climate on pollinator behaviour within commercial pak choi and onion seed crops. This examined the effect of climate on pollinator interactions with crops flowers and distances moved.

- NIWA national climate database to assess the affect of climate on pollinator abundances. Climate data was collected within fields for all pollinator behavioural studies.

We assessed the influence of climatic variables on abundance and behaviour of key pollinators. In addition, the influence of climate on overall crop pollinator diversity was also examined (see methodology for further details). A thorough exploration of the data-sets using summary statistics techniques revealed substantial variability in insect numbers around the trends with the climate factors identified as being associated with insect abundance. Empirical modelling of the data using the factors measured would therefore have been unlikely to produce a useful predictive model. We therefore used cubic smoothing splines to show the trends in the data from which conclusions on the potential impacts of climate change on crop pollinator were drawn. A more detailed data-set is required before a useful predictive model can be developed.

Industry workshop and report to Industry on Impact. Vulnerability and Adaption strategy.

Widespread communication of the findings of this research and the impacts on industry (vulnerability and Adaption) has been achieved through:

1) Industry workshop involving the Foundation for Arable Research and PGG-Wrightsons (held 11/3/12), also discussions with South Pacific Seeds (NZ) Smiths Seeds (Could not attend workshop due to commitments) and Seminis Vegetable Seeds (Nth Island).

Preliminary findings were presented at the workshop and risks to pollination and adaption strategies discussed. Key findings presented and discussed were:

- The importance of pollinator diversity to crop pollination
- Climate change predictions
- The interactions of climate variability to pollinator activity windows
- How does climate currently interact with pollinators and the impact on production
- What impact is climate change expected to have on pollinators and crop pollination

Issues of concern raised by the industry representatives that were beyond the scope of the research focused on:

1) The Influence of climate change on existing crops, were existing cropping areas likely to change?
2) How does climate influence the production of floral rewards such as nectar and pollen?
3) The potential development of new crops requiring insect pollination e.g. chicory in Canterbury?
4) Techniques to build resilient crop pollination such as building pollinator diversity (this is being tackled to some degree through research projects e.g. Building better biodiversity on cropping farms (SFF 12-01), Optimising Pollination (CAP10-55), Landscape Ecology (CAP10-71).

These issues raised by the industry representatives demonstrates their interest and concern regarding climate change impacts on their industries and demonstrates the need for new research beyond the scope of this project, that will help further with the development of adaption strategies.

Further Reporting to Industry and Scientific Audiences

Findings from this report were also presented to industry via the :

- Pollination and Apiculture Science Review, Tuesday 28 August 2012 .Mt Albert Research Centre, Auckland that included the Foundation for Arable Research, Zespri, NZ Avocado, Bayer, Gro Plus, National Beekeepers' Association, Comvita and Federated Farmers.

- New Zealand Pollination Conference, Mt Albert Research Centre, Auckland 21-22 June, 2012.

Presentations highlighting the need to build pollinator diversity to maintain and promote resilient crop pollination services in the face of climate change. The executive summary from the SLMACC report was presented as part of the Science Review document.

A presentation of the research findings will also be given to an international scientific audience at the 1st ApiEcoFlora Apimondia International Symposium, San Marino, 4 to 6 October 2012. The presentation is titled 'Climate and Pollinator foraging' and is scheduled for 5 October.

Paper accepted in the international journal: Basic and Applied Ecology

In conjunction with international collaborators, a paper with data from this research has been accepted in the Journal of Basic and Applied Ecology (impact factor: 2.669) with minor editing:

Rader R, Edwards W, Westcott DA, Cunningham SA, Howlett BG. Diurnal effectiveness of pollination by bees and flies in agricultural *Brassica rapa*: implications for ecosystem resilience.

A further manuscript based on work presented at the ApiEcoFlora Apimondia International Symposium is also planned in a special issue of Journal of Pollination Ecology (deadline 31 Dec 2012)

The research team are looking to publish several further publications from the research.

APPENDIX 4: Popular Report Summary

Climate change impacts on New Zealand insect crop pollination

Prepared for Ministry for Primary Industries.
By BG Howlett, RC Butler, WR Nelson and BJ Donovan,
The New Zealand Institute for Plant & Food Research Ltd

New Zealand relies on insects to pollinate crops worth at least NZ$2B annually to the New Zealand economy. These include crops grown for seed (e.g. carrot, radish, onion), fruit and vegetables (e.g. kiwifruit, avocado, tomato, squash, blueberries) as well as important pasture species (clovers).

Honey bees are often placed in crop fields to facilitate pollination. However, a combination of unmanaged bumble bee, native bee (Figure 1) and fly pollination can often exceed the contribution made by honey bees within pak choi and carrot fields. Pollinator activity can vary at different times of the day with species responding differently to climatic conditions (activity windows).

Figure 1 Native bee (*Leioproctus vestitus*) visiting a white clover floret.

Climate change will impact pollinator activity windows by altering foraging periods and behavior. By 2090, key crop growing regions such as Canterbury, Tasman, Hawkes Bay, Gisborne, Bay of Plenty and Northland are expected to have more than 20 extra days above 25°C compared to 1990 but receive more extreme weather events (Canterbury twice as many drought days, other regions increased summer storms and heavy rainfall events).

Surveys conducted in flowering pak choi and onion seed fields across New Zealand examined the abundance, diversity and behavior of pollinators. The data was matched with climatic data collected at or near the time observations were made, using within field recordings or data collected from nearby meteorological stations (within 10 km of fields).

Examples of pollinators responding differently to climate:

Honey Bee

Figure 2 Honey bee (*Apis melifera*) visiting a pak choi flower.

Honey bees were most abundant when conditions were sunny and temperatures exceeded 25°C. Honey bees are adept at foraging at high ambient temperatures but when temperature falls below 20°C find it increasingly difficult to maintain adequate body heat for flight. Increased temperatures brought about by climate change should extend their activity windows both during the day and the number of days suitable for foraging. However, increased storm activity and heavy rainfall events predicted for many regions in New Zealand may lead to increased unpredictability of their foraging times. This could particularly impact their pollination of crops with short flowering periods (e.g. some brassicas flower for just 2-3 weeks).

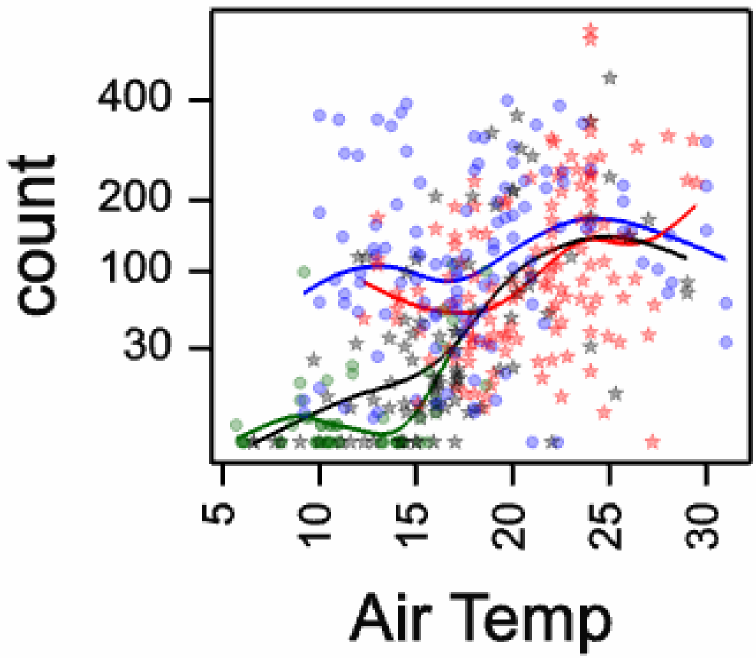


Figure 3 Counts of honey bees in onion and pak choi seed fields (each point represents one field observation time) versus temperature (ºC). The lines are smoothed trend lines of total counts within fields (black – onion between 6–9 am and 4–9 pm; red – onion between 10 am – 3pm; green – pak choi between 6–9 am and 4–9 pm; blue – pak choi between 10 am – 3pm), air temperature °C.

Bumblebees

Figure 4 Bumblebee (*Bombus terrestris*) visiting a flowering onion umbel.

The relative abundance of short tongued bumblebees (*Bombus terrestris*) on crop flowers showed the opposite trend to honey bees for the same climate variables. Their larger body mass helps maintain body heat when foraging in cooler temperatures, but they are less efficient at regulating their temperature at higher temperatures compared to honey bees. The increased temperatures brought about by climate change are likely to reduce the window of activity of bumblebees, both during the day and the number of days suitable for foraging. However, compared to honey bees, they will be more tolerant to increased storm activity.

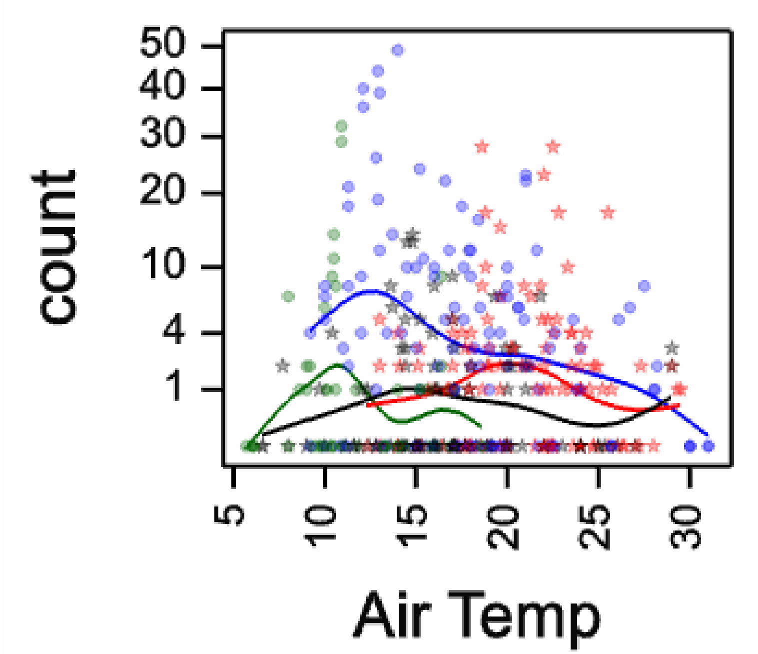


Figure 5 Counts of short-tongued bumblebees in onion and pak choi seed fields (each point represents one field observation time) versus temperature (ºC). The lines are smoothed trend lines of total counts within fields (black – onion between 6–9 am and 4–9 pm; red – onion between 10 am – 3pm; green – pak choi between 6–9 am and 4–9 pm; blue – pak choi between 10 am – 3pm), air temperature °C.

Flies

Figure 6 Green soldier fly (*Odontomyia sp.*) visiting a flowering onion umbel.

Different fly pollinators showed different responses to climate. Some species such as New Zealand orange hoverflies (*Melanostoma fasciatum*) were more abundant at temperatures below 20 °C, while others [e.g. blow fly species (*Calliphora* spp.), drone flies (*Eristalis tenax*) and green soldier flies (*Odontomyia* spp.] foraged across a wide range of climatic conditions. Many fly species can fly at lower body temperatures than bees. They also tend to shelter closer to crops allowing them to begin foraging quickly when climatic conditions become suitable. They are often dominant pollinators in cooler moister habitats. Flies capable of foraging under wide climatic conditions are likely to be among the most resilient pollinators as the climate changes.

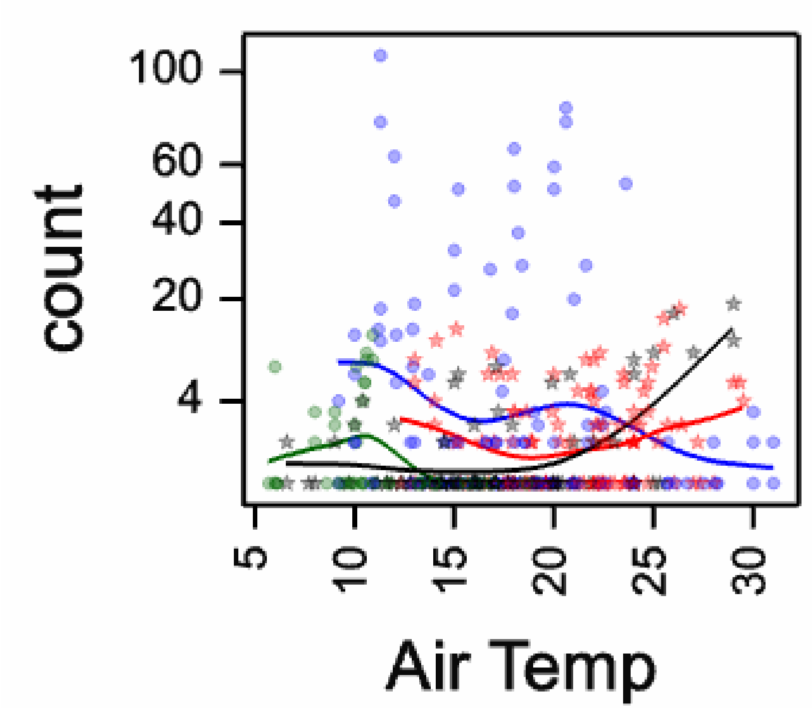


Figure 7 Counts of green soldier flies in onion and pak choi seed fields (each point represents one field observation time) versus temperature (ºC). The lines are smoothed trend lines of total counts within fields (black – onion between 6–9 am and 4–9 pm; red – onion between 10 am – 3pm; green – pak choi between 6–9 am and 4–9 pm; blue – pak choi between 10 am – 3pm), air temperature °C.

Maintaining crop pollination services with changing climate

Climate change will have impacts on the activity windows of different pollinating species thereby influencing their importance as crop pollinators, but climate change is also likely to alter:

- pollinator lifecycles, distributions and their interactions with pests and diseases
- the timing and supply of nectar and pollen by crop plants
- the crop species grown and their locations.

These topics require further evaluation to more accurately assess the impact of climate change on the production of insect pollinated crops in New Zealand. Despite this, a key strategy should be to build pollinator species diversity to ensure pollinator activity is maximized under changeable and highly variable climatic conditions. This requires a focus on practical management solutions targeting a range of species already identified as key pollinators.

Acknowledgements

We thank Smith Seeds Ltd and associated farmers who provided seed for a pak choi trial and allowed access to pak choi crops. Seminis Vegetable Seeds NZ Ltd, South Pacific Seeds (NZ) Ltd and associated farmers for access to onion crops. Samantha Read, Heather McBrydie, Samantha Rowland (Plant & Food Research), Maxime Musso, Charles Rollet (Agrocampus Ouest) for assisting with field work. Nick Pyke and staff from the Foundation for Arable Research for useful discussions and assistance with field work. This project was funded by SLMACC C11X1101.