

# Status and Trends of Pollinator Health in Ontario



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## DISCLAIMER

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The views and opinions expressed in this report are solely those of the authors, and may not necessarily reflect the position of OMAFRA or other Ontario government entities. This document was initially prepared and submitted to OMAFRA for internal government use on April 6, 2016. The authors have subsequently updated the report where possible ahead of public release to incorporate material published since April 2016. However, the highly dynamic nature of research on pollinators and pollination means these more recent publications have necessarily not been as comprehensively and exhaustively reviewed as material available prior to April 2016.

A note on accessibility, this document is available in alternate formats upon request. Please contact Stephanie Craig at [scraig02@uoguelph.ca](mailto:scraig02@uoguelph.ca) or 519-824-4120, Ext. 56832

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## EXECUTIVE OVERVIEW

The main objective of this project was to provide the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) with a comprehensive review of the current scientific evidence base relating to the status and trends of pollinator health in Ontario. This report highlights the major environmental stress factors likely to be affecting pollinator health in the province, assesses the strength of evidence supporting these trends, the likelihood of interactions between stress factors, and identifies current knowledge gaps.

While bee species are typically the main pollinators for many wild plants, butterflies, moths, wasps, flies, beetles and hummingbirds are also important to the pollination process. Therefore, in this report, we focus on the status and trends of managed and wild bee populations in Ontario, while also providing information on the status of other pollinator groups where it exists.

This report is intended for use as a scientific evidence base to inform the Ministry's near-term policy and program options. Project outcomes include provision of the following: 1) a summary of the current knowledge on the status of pollinators and the pollination services they provide relevant to Ontario, 2) an overview of the areas of uncertainty and knowledge gaps that could be used to inform decisions relating to future research priorities (e.g. through University of Guelph agreement, *New Directions* program and/or other collaborative research), and 3) final scientific report outlining the scientific evidence base on current pollinator health, trends and the impacts of existing conservation/remediation strategies for pollinators.

## EXECUTIVE SUMMARIES

### Status and Trends of Pollinators in Ontario

Pollinators are essential to agricultural production (particularly fruit, vegetable and nut crops) and maintaining the health and diversity of wild plant communities. There is well established evidence showing declines in pollinators around the world (reductions in species richness on a national/ landscape scale, range contractions of specific pollinator species, and reduced pollinator abundance) with associated evidence of reductions in crop pollination services leading to reduced yield (pollination deficits). This raises concerns for agricultural production and maintenance of biodiversity for Ontario, Canada, and around the world.

Animals that provide pollination services are very diverse, including bees, flies, wasps, butterflies and moths, beetles and hummingbirds. Ontario is a Canadian pollinator biodiversity hotspot, containing 420 of 855 (49%) nationally recorded bee species – the highest bee diversity of any province. It is also the last province in which the formerly widespread Rusty patched bumble bee (*Bombus affinis*) was most recently found (when a single individual was observed by Dr. Sheila Colla at the Pinery Provincial Park in 2009). As bees rely on flowers to provide all their food (nectar and pollen) they are typically the most important pollinators for the majority of plant species. Bees vary considerably in their ecology and life-history: the vast majority of species (810/855 or 95%) are solitary bees, while bumble bees (44/855 or 5%) and honey bees (1 species) form colonies of up to 65,000 individuals respectively. Two bee species (the western honey bee *Apis mellifera*, the bumble bee *Bombus impatiens*, are commercially reared and used as managed pollinators for agriculture in Ontario, while the remaining wild bees pollinate crops and wild flowers within flight range from their nest sites (e.g., undisturbed ground or cavities, such as dead wood).

This report highlights the major environmental stress factors likely to be affecting pollinator health in the province (land use change, climate change, agrochemical usage, pests & pathogens, and management practices), assesses the strength of evidence supporting these trends, the likelihood of interactions between stress factors, and identifies current knowledge gaps.

### Agriculture Reliance on Pollinators

Pollinators are essential for agriculture as 76% of the leading global food crops (including many fruits, vegetables and seed crops) are pollinated by animals. In addition, pollination is essential for maintaining wild flower diversity in both managed and agricultural ecosystems. Currently populations of at least 78 Ontario plant species may be in decline because they receive insufficient pollination, however evidence for this is currently speculative. Little is known about the pollinators of rare plant species, which is a cause for concern given that pollination is essential for the long-term survival of most flowering plant species.

In Ontario there are 32 economically important crops, representing 6 major types (orchard fruit, berry fruit, field fruit and vegetables, forage and oilseeds, greenhouse crops, and other crops) that require insect pollination. There is considerable evidence demonstrating the importance of flower visits by insects to crop pollination globally, particularly for the 6 major crop types found in Ontario. An emerging theme from this global evidence is that proximity of natural or semi-natural habitat to agricultural lands is frequently linked to



increased yield in a range of crops, although such information is not available for Ontario. These insect dependent crop types represent approximately 2.67 million hectares of land in Ontario. However, in comparison to the number of studies investigating pollination of crops relevant to the province from the USA and Europe, there is considerably less evidence from Ontario or Canada. In addition, information on pollinator contribution to crop pollination is dated or generally lacking for many Ontario crops (including soybeans).

Most pollination research has focused on investigating the importance of honey bees for agricultural crops, however there is well established evidence demonstrating the importance of wild pollinators for increased fruit set in both wild plants and a range of economically important crops around the world. Currently, research on the importance of wild pollinators for crop pollination in Ontario is severely lacking. This is concerning given wild pollinators are linked with increased fruit set in at least 34% (11 of 32) of the insect dependent crops in Ontario. The financial implications of this knowledge gap are unclear because it is unknown how much the estimated value (\$895 million/year) of pollination services to crops in the province are provided by wild pollinators.

### Impacts of Existing Pollinator Management and Conservation Strategies

Currently, there is limited legislation in Ontario and Canada to protect pollinators. The Ontario Bees Act addresses solely honey bees, and often protects the rights and liabilities of beekeepers over the health of honey bees themselves. The Endangered Species Act also protects nine pollinator species at risk. Additional legislation, directed at both managed and wild species, could be helpful to protect pollinators in Ontario, Canada, and around the world. The most important consideration with creating new conservation policies and legislation are that they are based on rigorous scientific evidence; they are evaluated for their efficacy and revised as necessary to improve utility.

In an effort to protect pollinators, conservation strategies can be implemented in agricultural areas, urban environments, and other sensitive lands. Selection and implementation of specific strategies will depend on conservation priorities, and may differ substantially if the goal is to enhance pollination of particular crops, maintain wider pollinator biodiversity or specifically target the recovery of pollinator species at risk. The best conservation strategies may deliver more than one of these goals, and also provide suitable habitat for other beneficial arthropods (e.g. spiders, predatory beetles and parasitoid wasps that can provide pest bio-control), birds and wildlife in the landscape.

Most research has focused on adding and restoring pollinator habitat, typically by planting more abundant and diverse floral mixtures, and providing or enhancing nesting sites and suitable larval host plants, and the evidence has shown these strategies can be highly effective at increasing pollinator abundance and species richness. Restoring established habitat, as well as generating new habitat through innovative means (e.g., creating pollinator gardens on old landfill sites or suitable habitat along roadsides, railways or under power lines) improve provision of pollinator forage and nesting sites. Evidence from USA and Europe suggest at a landscape scale that conservation strategies need to consider connectivity of suitable habitat patches at scales relevant to foraging and dispersal. These scale considerations are also likely to be important for enhancing crop pollination by wild pollinators. The lack of critical information on the distribution and biodiversity of pollinators in Ontario represents a major obstacle to developing appropriate and sustainable conservation strategies.

## INTRODUCTION

### The Importance of Pollination

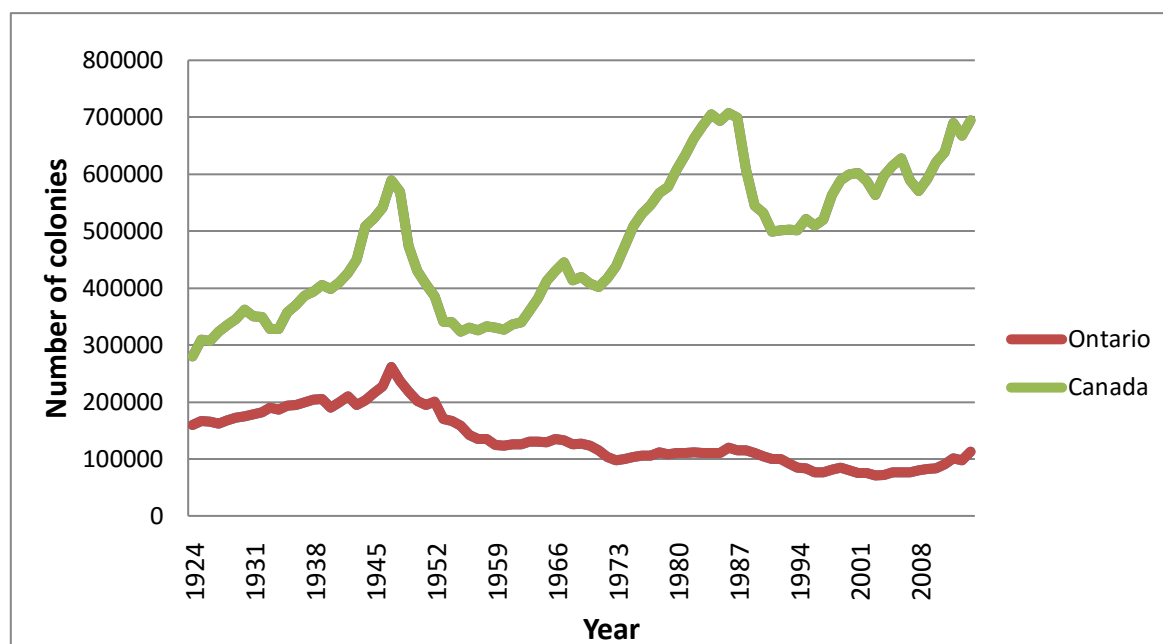
Pollination is arguably one of the most critical global ecosystem services with approximately 87.5% of the world's flowering plant species pollinated by animals (Ollerton et al. 2011). Pollinators are essential for agriculture as 76% (87/115) of the leading global food crops (i.e. fruits, vegetables, seed crops, etc.) are pollinated by animals (Klein et al. 2007). Crop pollination by insects specifically underpins around \$ 235–577 billion USD of global crop production each year (IPBES 2016; Lautenbach et al. 2012; Potts et al. 2016).

Bees are the most specialized insect pollinators due to the variety of particular morphological traits (e.g. different tongue lengths and evolution of pollen baskets) that allow them to collect and store pollen (Patricio-Roberto and Campos 2014). Pollination by bees in agroecosystems in North America is worth billions of dollars each year (Kevan and Phillips 2001) with both direct and indirect influences on the global economy (Committee on the Status of Pollinators in North America 2007; Gallai et al. 2009). Honey bees (*A. mellifera*) are the most economically valuable pollinators worldwide (Klein et al. 2007), accounting for 80% of global agricultural crop pollination (Carreck and Williams 1998); however, it is known that wild bees are more effective pollinators on a per bee basis (Breeze et al. 2011; Garibaldi et al. 2013). Specifically in Ontario, the combined populations of managed honey bees and bumble bees generate about \$895 million of the roughly \$6.7 billion in sales for agricultural crops grown in the province each year (OMAFRA 2014b).

Along with its crucial economic role, pollination by bees also has an important ecological role in maintaining wild flower diversity for both natural and agricultural ecosystems. Furthermore, non-crop flowers can increase crop yield by providing additional food for pollinators (Sheffield et al. 2008b). More generally, pollination helps to sustain all the other organisms in an ecosystem that depend on resources ultimately obtained from flowering plants (e.g. seeds for birds).

### Managed Pollinators

The increase in crop production since the start of the agricultural revolution has warranted the use of managed bees to enhance pollination for increased crop yield. Honey bees (*A. mellifera*) are the most common and widespread managed pollinator in the world, but other bee species have become managed by humans in the past 40 or so years (Parker et al. 1976, 1987; Velthuis and van Doorn 2006) and it is anticipated that more species will be used as time and agricultural demands progress. In Ontario, there is one managed bee species that is used in addition to honey bees: the managed bumble bee *B. impatiens*, used mainly for greenhouse pollination of tomatoes and peppers (Kevan et al. 1991; Whittington and Winston 2004).



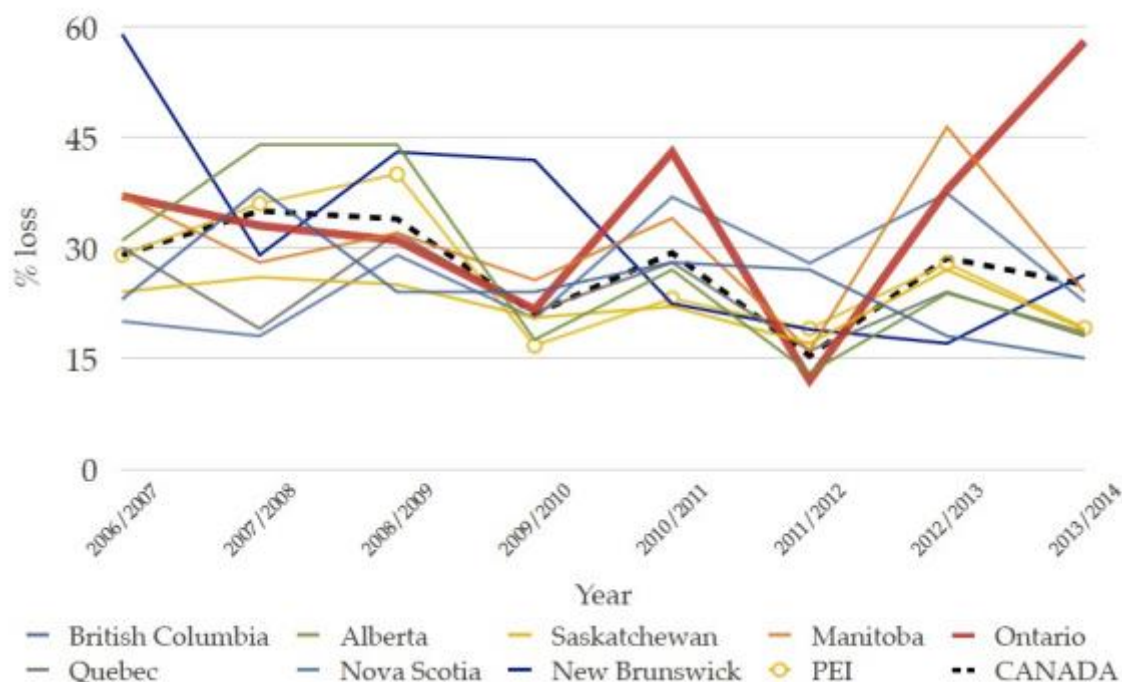
**Figure 1.** Total number of managed honey bee colonies in Ontario and Canada over a 90 year period (1924-2014) (Statistics Canada 2014b).

### Honey Bees (*Apis mellifera* L.)

The Western honey bee (*A. mellifera* L.) is the most common managed pollinator in the world (Mallinger et al. 2015). Honey bees have been used by humans for thousands of years for crop pollination and have been domesticated for at least 4,000 years (Abrol 2012a). To date, Ontario has over 3,000 beekeepers that manage over 100,000 colonies (OMAFRA 2014a). Current status reports of honey bees in Ontario show that they are experiencing stress. Overall, the number of colonies in Ontario has shown a decreasing trend over time (Figure 1), and winter and summer losses have exceeded the level reported as sustainable by beekeepers for the past decade. The overall trend in Canada is that overwintering losses are decreasing (Figure 2). Compared to other provinces, Ontario experienced the highest overwintering loss last year, where 58% of colonies did not survive until spring (Kozak 2015b). In recent years, overwintering losses in Ontario have exceeded those of other Canadian provinces and those experienced by the USA (Figures 2, 3).

Honey bees are social insects and have been studied more extensively than any other insect pollinator in the world. They are highly versatile pollinators capable of pollinating over 60 plant families, including fruits, vegetables, flowers, forage crops for livestock, and oilseeds (Southwick and Southwick 1992). However, despite their ability to pollinate a variety of crops, they are often not the most effective pollinators (Breeze et al. 2011; Garibaldi et al. 2013). Their inefficiency as individual pollinators is usually compensated for by placing multiple hives in one field, thus saturating these fields with foragers effectively outnumbering the native bees. Other benefits of using honey bees as pollinators are that they have been domesticated (for honey production) for hundreds of years and are easy to transport. Their large foraging range, of up to 15 km (Beekman and Ratnieks 2000), allows them to pollinate the middle of fields, whereas wild bees have much more restricted ranges (Gathmann and Tschardt 2002), making them capable of only pollinating the crop edge. Several studies have demonstrated that this widespread species, which has in

recent years approached a global distribution, is outcompeting native bees and serving as a causal factor for native bee population declines (reviewed in Paine 2004). As demands for animal pollinated crops continue to rise dramatically around the world one study suggests that numbers of honey bee colonies may not be able to cope with the additional pollination requirements (Mallinger et al. 2015). This information, combined with the knowledge that maximum pollination is best achieved when honey bees are used in conjunction with wild bees (Aizen and Harder 2009; Garibaldi et al. 2013; Greenleaf and Kremen 2006b), serves as incentive to promote the use of wild bees and other managed bees in pollination services in addition to honey bees.



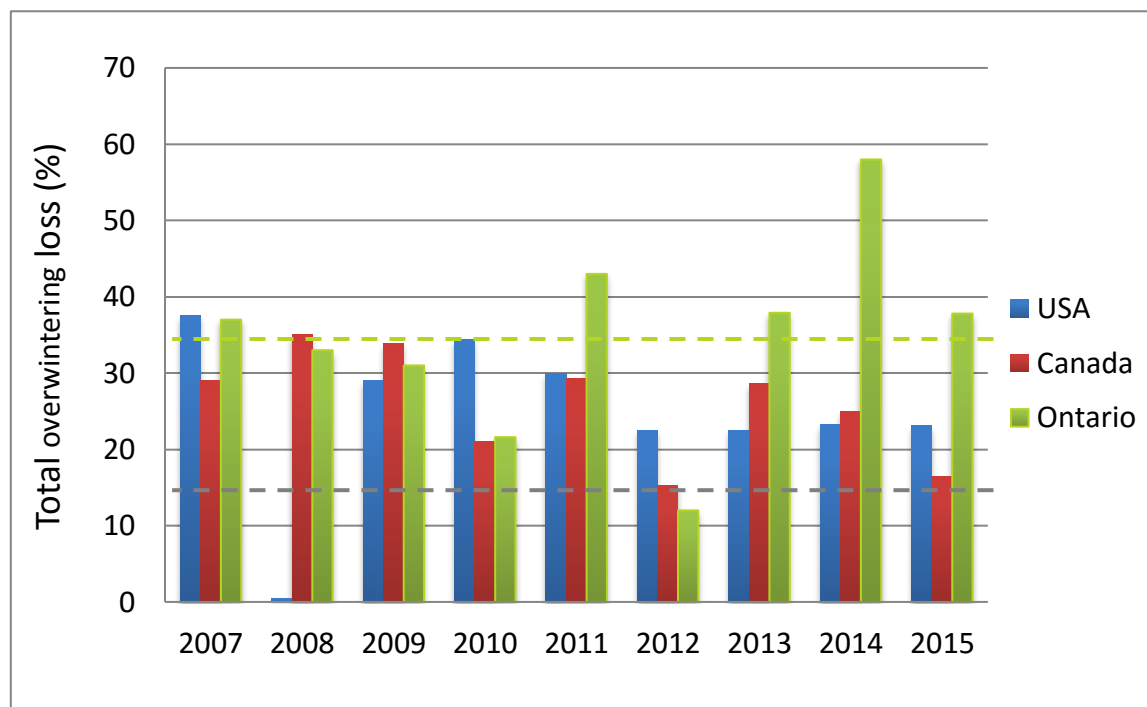
**Figure 2.** Percentage of overwintering honey bee colony losses in Ontario compared to other provinces and the whole of Canada (dashed black line) from 2007-2014.

### **Alfalfa Leafcutter Bee (*Megachile rotundata* Say)**

The ALCB was accidentally introduced into North America in the 1940's and has since become the most effective and intensively managed solitary bee species (Pitts-Singer and Cane 2011). Since first being detected in the USA, this leafcutter bee has transformed the alfalfa industry significantly increasing crop yields (Pitts-Singer and Cane 2011; Richards 1987).

To date, no other solitary bee has been as intensively managed as the alfalfa leafcutter bee. The management success of this species has been attributed to several traits: use of leaves for lining nests, ready acceptance of cheap nesting material, pollination efficiency, and emergence synchrony with alfalfa bloom (Pitts-Singer and Cane 2011). Farmers order bees as pupae and refrigerate them until they are ready for them to emerge as adults. Transferring the pupae to warmer temperatures signals their eclosion, allowing farmers to time their emergence with peak alfalfa bloom periods (Richards 1987). Alfalfa production is increasing in Canada. As a perennial crop, it is less expensive to plant than annual crops like wheat and barley. Many Canadian farmers are making the switch to alfalfa because it is less expensive

and also to meet the increasing demand for animal feed (Statistics Canada 2006). Honey bees are ineffective pollinators of alfalfa in the Canadian climate (Richards 1987), so the maintenance of these managed pollinators is very important for Ontario agriculture.



**Figure 3.** Honey bee overwintering losses in Ontario compared to Canada and the USA from 2008 to 2015. Blue, green, and red bars represent the percentage of total overwinter loss for the USA, Canada, and Ontario, respectively. Green dashed (horizontal line) indicates the average overwintering colony loss rate over this period in Ontario (35%), and grey dashed line indicates the 15% annual overwinter colony loss rate deemed sustainable by the Canadian beekeeping industry.

### Blue Orchard Bee (*Osmia lignaria* Fab.)

Similar to the ALCB, the BOB is one of the most effective and intensively managed solitary bee species. However, unlike ALCB, *Osmia lignaria* is native to North America and therefore considered to be the most successful native managed solitary bee species in Canada and the USA (Sedivy and Dorn 2013; Sheffield et al. 2013a). The BOB is solitary, however it tends to nest in aggregations (Bosch et al. 2006). This nesting strategy has made the species most desirable for commercial pollination, as it is relatively simple to collect and rear at large scales. These bees are relatively low maintenance and can live in a variety of artificial nest sites (Sedivy and Dorn 2013). Females are more effective pollinators than males, and can lay up to 30 eggs in their lifetime (Bosch and Kemp 2002). *Osmia lignaria* is active from spring to early summer making it an effective pollinator for tree fruit crops, such as apple and cherry (Bosch et al. 2006); however, their flight period is known to be considerably longer than the blooming period of the tree fruit crops they pollinate (Sheffield et al. 2013a). Ensuring the presence of blooming foraging plants during the entire flight period for this species may aid in safeguarding quality pollen and nectar resources while species are still active after tree fruit bloom. *Osmia lignaria* are very efficient pollinators, and their preference for flowers in the Rosaceae family (e.g., almond, apple, cherry, pear, etc.) over other flowers make them effective at pollinating crops of interest over nearby weeds (Sedivy and Dorn 2013). Beekeepers or farmers can

also exert some control over the regions where these bees are pollinating, as they prefer to forage near their nesting sites (Sedivy and Dorn 2013).

### **Bumble Bees (*Bombus* spp.)**

In recent decades, bumble bee colonies have been introduced to enhance greenhouse and soft fruit pollination in North America, South America, Europe, Asia and New Zealand (Velthuis and van Doorn 2006). Bumble bee species distributions are largely limited to the temperate northern hemisphere and there are 25 species found in Ontario (Colla 2016). The native bumble bee *B. impatiens* has been domesticated and is largely used in greenhouse pollination for crops like tomatoes and peppers. Bumble bees form smaller colonies (about 200-300 workers) than honey bees. Honey bees, with large colonies, longer foraging ranges, and more generalist floral preferences, do not do well in closed spaces like greenhouses without becoming disoriented and aggressive (Graystock et al. 2014). The small colony size of bumble bees, and their efficiency at pollinating soft fruits, allows them to be ideal for closed spaces like greenhouses. In fact, managed *Bombus* are the most important pollinators for greenhouse produce because bumble bees can sonicate (buzz pollinate) tomatoes – something honey bees are unable to do. This is critical to Ontario, as this province grows a larger area of greenhouse produce (12 million m<sup>2</sup>) than any other, making it a leader in greenhouse vegetable production in Canada and contributing 55% of all greenhouse products (Statistics Canada 2008). An emerging problem due to managed *Bombus* is that greenhouses are not entirely closed systems, meaning that some managed bees visit and pollinate flowers outside and come into contact with wild *Bombus*. This contact facilitates the transfer of pests and pathogens that can be more prevalent in managed bees (Colla et al. 2006).

### **Wild Pollinators**

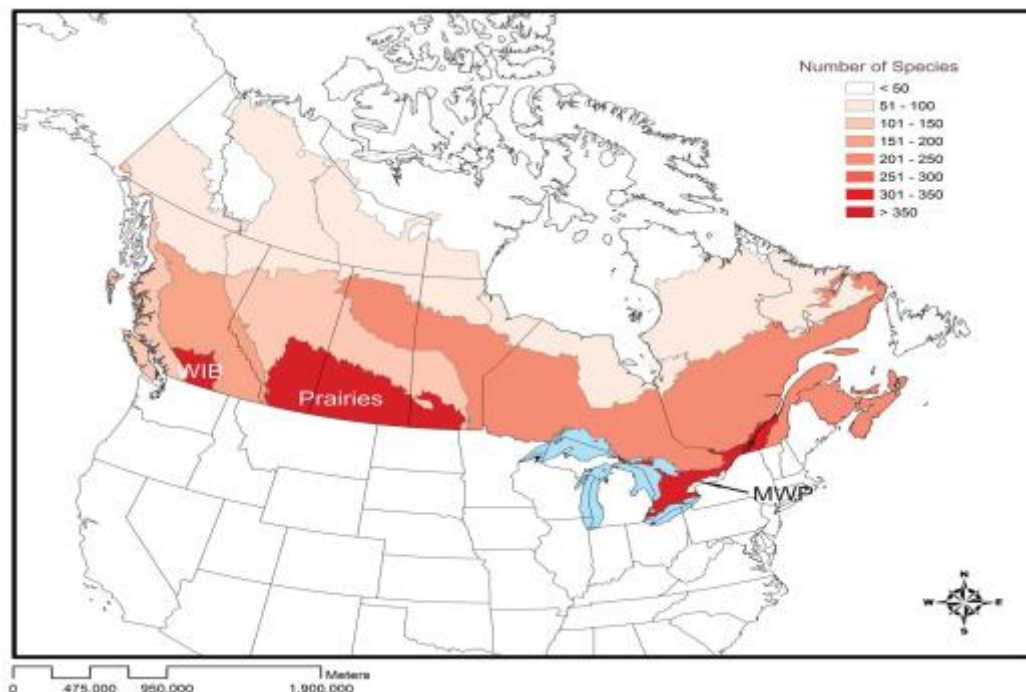
Wild pollinators are known to be present anywhere insect-pollinated flowers are located (Winfrey 2010; Woodcock 2012) and the pollination service they provide is delivered at no-cost to humans. Species richness and abundance of wild pollinators can be encouraged in habitats by maintaining a variety of nesting and floral resources (Westphal et al. 2003). Maintaining species richness and abundance in habitats is crucial, particularly in agroecosystems where it has been documented that wild insect visitation enhances fruit set by twice as much as an equivalent increase in honey bee visitation (Garibaldi et al. 2013). In recent decades, however, declines in wild pollinators have been reported worldwide (Biesmeijer 2012; Kremen et al. 2007; Potts et al. 2010). Declines in wild pollinators undeniably impact both their capacity to pollinate wild plants on which our ecosystems depend and their potential to assist with crop pollination (Brown and Paxton 2009; Kremen et al. 2007; Winfrey 2010).

### **Wild Bees**

Recent estimates of Canadian bee diversity determined that Ontario is home to some 420 of the 855 bee species found in Canada, making this province a national bee biodiversity hotspot for Canada (Sheffield et al. 2011; Figure 4).

In eastern Canada, with Ontario data included, the only studies that have assessed actual native bee declines have focused on bumble bees (Colla and Packer 2008; Colla et al. 2012). A North American study by Colla et al. (2012) surveyed *Bombus* spp. using museum specimens and assessed one species as critically endangered (the Rusty Patch bumble bee, *Bombus affinis*), six species as endangered, and four species as vulnerable.

However, not all species are experiencing population declines. Species responses are variable, and some, such as *B. impatiens*, a historically common species in Canada, are increasing in both population and range (Colla et al. 2012; Goulson et al. 2008). The extent to which trends in one geographic local are reflected globally, and the extent to which trends in *Bombus* spp. are reflected in other groups, are mostly uncertain at this time and remain to be tested (Winfree 2010).



**Figure 4.** The number of wild bee species (in increments of 50) recorded in different Canadian ecoregions. More intense shades of red indicate higher species richness. Three ecoregions containing grasslands are labelled: Prairies, Western Interior Basin (WIB), and Mixed Wood Plains (MWP) (reproduced, with permission, from Sheffield et al. 2011).

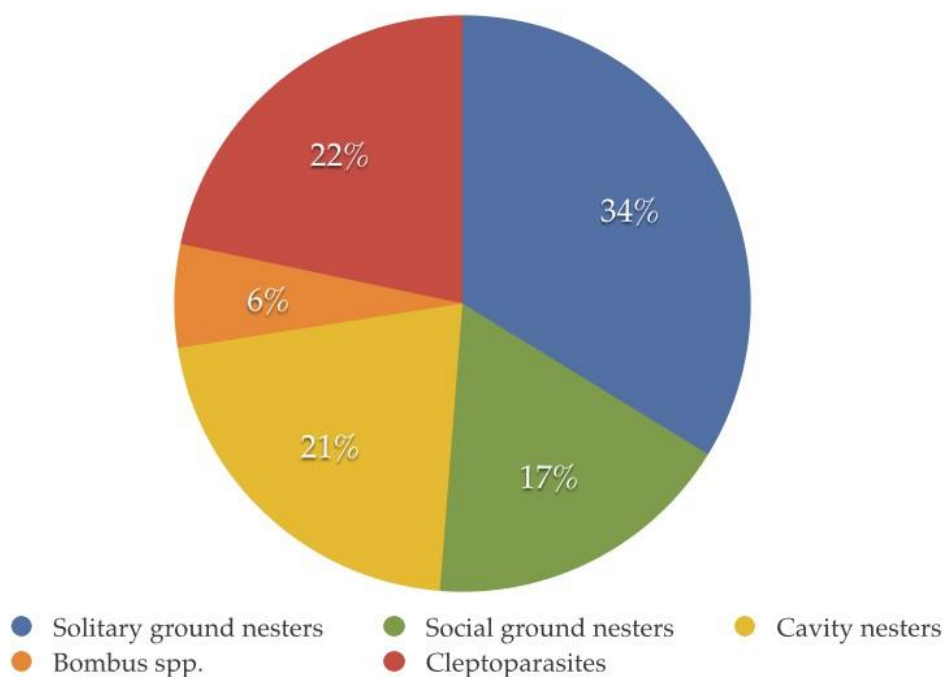
In North America, a recent study with access to a relatively unique dataset compared current native bee populations to those recorded over 120 years ago and found that 50% of historical bee species were extirpated (Burkle et al. 2013). Both Burkle et al. (2013) and Biesmeijer et al. (2006), as well as others (see Ebeling et al. 2008; Fontaine et al. 2006; Potts et al. 2010 for additional examples), also detected associated declines in pollination function and plant community richness, respectively. These findings are concerning because they indicate that the loss of pollinator species can have cascading effects on their associated habitats and communities. Certain pollinating groups, such as *Bombus* spp., are comparatively well studied and declines, extirpations and extinctions have been reported for some species within this genus (Cameron et al. 2011; Colla and Packer 2008; Goulson et al. 2008; Williams and Osborne 2009).

Species richness and diversity are understood to be fundamental ways of indicating changes in biodiversity in time and space; however, these metrics are less suitable for evaluating how community composition could be affected by anthropogenic change. Using functional guilds to assess the status of bees in habitats throughout Ontario provides greater accuracy than examining bee communities as a whole (Nardone, 2013; Neame et al. 2012; Richards et al. 2011; Tilman and Lehman, 2001; Williams et al. 2010).



Functional diversity is described as the diversity of traits of species, however it is often used to represent the diversity of species' functions and/or guilds within an ecosystem (Cadotte et al. 2011; Petchey and Gaston 2006). Unlike traditional metrics used to measure species richness and diversity, metrics of functional diversity provide a mechanistic link between species and environmental factors (Cadotte et al. 2011). Figure 5 shows the percentage of species representing each functional guild. It is clear that solitary and social ground nesters are the most common groups of wild bees found in Ontario, however there is limited information on how these species respond to environmental variation.

While several reviews of the status and trends of pollinators have been completed, unlike previous reports, here we assess bee community response to potential drivers by breaking the bee community into functional guilds (solitary ground nesters, social ground nesters, cavity nesters, bumble bees and cleptoparasites) to provide an overview of the scientific evidence base relating to the status and trends of pollinator health in Ontario. Incorporating an assessment of functional diversity into studies allows for a deeper understanding of species' response to anthropogenic change and in turn the creation of more accurate conservation strategies for species landscapes.



**Figure 5.** Percentage of bee species representing functional guilds: solitary ground nesters, social ground nesters, cavity nesters, bumble bees and cleptoparasites found in Ontario.

## Other Pollinators

In addition to bees, other pollinators in Ontario include birds, wasps, butterflies and moths, and beetles. The only bird pollinator in Ontario is the ruby throated hummingbird *Archilochus colubris*, which feeds on floral nectar to meet its high carbohydrate demands, during which process it will inadvertently pollinate flowers. They are very common in Southern Ontario and less common in Northern Ontario, and their provincial population is stable to slightly increasing due to increased planting of flower gardens and providing nectar feeders (Sandilands 2010). To our knowledge, there is no research on how their health or abundance is impacted by the four stress factors outlined above (see page 23).



Butterflies are well-researched pollinators, but are actually not very efficient at collecting and distributing significant quantities of pollen. They are, however, very reliant on floral nectar as a food source (Kerr 2001). Because of this mutualistic relationship, stress factors affecting nectar (such as agrochemicals) and flower blooming (such as climate change) may impact these pollinators. Many flies in Ontario, especially from the family Syrphidae and Bombyliidae, pollinate flowers (Woodcock 2012). Some generalist flower visitors are equal or more effective than bees at pollinating (Kearns 2001), but the basic biology of most species, and the knowledge of how stress factors are affecting their populations in Ontario are unknown. Furthermore, there is no evidence that documents fly pollinators in North America are experiencing declines (Kearns 2001).

In Ontario, wasps inadvertently provide minor pollination, but are not officially categorized as crop pollinators. Furthermore, there are no beetles in Ontario that pollinate crops, but some species do pollinate flowers (Woodcock 2012). To our knowledge, there are no studies that directly examine the effect of the four stress factors on these species' health and abundance.

## METHODS FOR COMPREHENSIVE REVIEW

Our literature search for the comprehensive review was conducted using ISI Web of Science from February 2015 to April 2015. We did not apply any limits to the timespan in our search, as it is important to include all current and historical documents. Historical perspectives and trends are crucial to examine potential long-term changes in species diversity, species ranges, and population sizes for key indicator taxa (e.g. honey bees and bumble bees). Articles in any language other than English were excluded, as well as conference abstracts for which no corresponding publications existed.

We also cross-referenced our search with Google Scholar when appropriate for additional peer-reviewed articles or grey literature that were not listed by ISI Web of Science. Once database searches were completed and all articles were collected, we also scanned their reference lists for any additional papers that appeared relevant to add to our reference library. For a complete list of search terms for each pollinator and stress factor used in ISI Web of Science and Google Scholar, please see Appendix A.

**Table 1.** The overall number of peer reviewed articles and grey literature reports found through the databases searches and personal searches as of May 4, 2015.

Search Category	Wild Bees	Managed Bees	Other Pollinators*
Total number of studies	2,511	14,558	1,634
Land Use Change	811	1072	528
Climate	233	1100	317
Agrochemicals	568	2,045	387
Pest and pathogens	636	9,875	326
Management Practices	187	325	14
Extra Search (Loss, Death, Decline etc.)	7 6	141	62

\* Other pollinators include hummingbirds, wasps, butterflies, and flies

**Table 2.** The overall number of peer reviewed articles and grey literature reports found through the databases searches and personal searches for crop pollination as of August 30, 2015.

<b>Search Category</b>	<b>Wild Bees</b>	<b>Honey Bees</b>	<b>Other Managed Bees</b>
Total number of studies	1,618	8,388	2,343
Pollination Services (pollination services, ecosystem services, etc.)	935	14	290
Agriculture (contribution, biodiversity, etc.)	777	3,358	465
Fruit and Field vegetables	98	584	153
Orchard	101	768	116
Berries	64	353	82
Forage and Oilseeds	217	1558	313
Greenhouse	13	157	58
Other crops	11	72	3
Extra Search (nesting sites, resilience, etc.)	129	554	118

Our systematic peer-reviewed literature search and sourcing of government grey literature resulted in a total of 61,715 unique studies. The breakdown of these studies into the various stress factors for wild bees, managed bees, and other pollinators is shown in Tables 1-3. The majority of studies were conducted in Europe (52%), followed by the USA (35%), followed by Canada excluding Ontario (10%), followed by Ontario (2%), followed by other countries (1%). The exact number of studies from each location is represented in Figure 6. It is important to note there are so few studies from ‘outside’ countries because many of the search terms were specific to Ontario.

**Table 3.** The overall number of peer reviewed articles and grey literature reports found through the databases searches and personal searches for Conservation Strategies as of Aug 31, 2015.

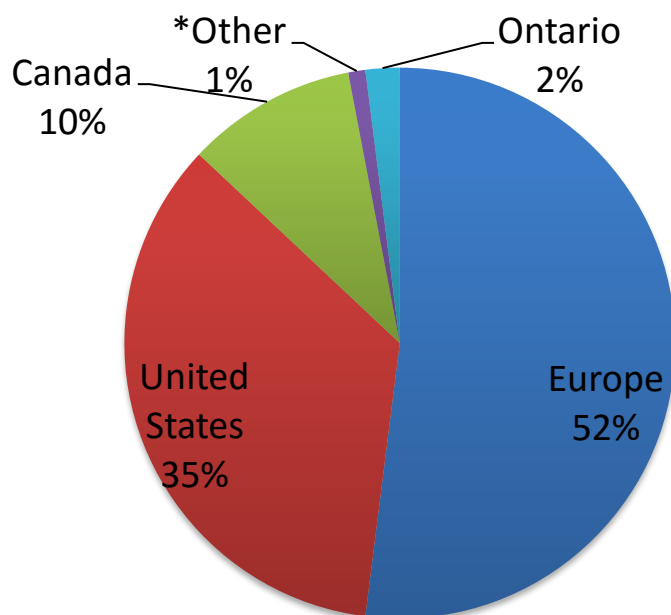
<b>Search Category</b>	<b>Total number of Studies</b>
Conservation (strategy, assessment, plan, etc.)	4,338
Ecosystem (service, function, value, role, etc.)	3,032
Agri-environment scheme (strategy, management, farm management, etc.)	268
Government (policy, congress, action plan, not for profit, non government, etc.)	3,575
Extra Search (farm bill, trap nest, ecological role, rights of way, etc.)	2,375

### Sourcing Relevant Grey Literature

When applicable, grey literature was sourced from key government agencies in Canada with assistance from OMAFRA colleagues, the Ministry of the Environment and Climate Change (MOECC), and the Pest Management Regulatory Agency (PMRA). Additional grey literature was obtained from foreign governments and multinational organizations (e.g. European Commission (EC) or European Food Safety Authority (EFSA)), Non Government Organizations and industry for reports, datasets, etc. This work required extensive liaison with academics, industry and government contacts locally for their knowledge and understanding of the datasets that exist and how to access them.

### Evaluating Studies for Relevancy to Ontario

Deciding what studies provided the most relevant information to convey a picture of historical and current pollinator health in Ontario was imperative. We analyzed all studies identified through our peer-review and grey literature searches for their scientific rigour, results, robustness of conclusions, and critical relevance of their findings to Ontario conditions. To determine relevancy for Ontario, studies were included if they met the following criteria: 1) they were geographically close (within Ontario, Canada, USA) or similar to Ontario (Western Europe), 2) they examined species of pollinators that are found in Ontario, 3) they examined crops that are present in Ontario, 4) they studied pests and/or pathogens that affect pollinators in Ontario, 5) they studied agrochemicals that are used in Ontario, 6) they examined management practices that are utilized in Ontario.



**Figure 6.** Pie chart representing the geographic locations and the percentage of the total unique studies retrieved through the systematic search of the peer-reviewed and grey literature. \*Studies from other countries relevant to Ontario.

Of the 61,715 unique studies collected from the literature search, 5,836 were relevant to Ontario. These studies contained monitoring reports, empirical experiments, field studies, case studies, background information papers, and review articles. All studies except background information papers and review articles were further analyzed for overall quality following the procedure outlined below.

### Assessing Studies for Overall Quality

Overall quality of the study was assessed by assigning scores based on scientific rigour. Studies earned one point for clearly accomplishing each of the following criteria:

1. The study examined an outcome to pollinator health or population (e.g., mortality rates, changes in species richness or diversity, changes in gene expression).
2. The study had a control.
3. The study presented measures of variability with which to calculate effect sizes.
4. The study had more than one replication per treatment, and the number of replications was included.
5. The study documented the sample sizes used for analyses.
6. The study captured the entire flight period of the species investigated. For example, if a field study is examining all wild bee species it must collect bees from the beginning of spring to the end of fall, as different species are active during different seasons.
7. The study used conditions that were realistic to nature. For example, studies examining the effect of pesticides on pollinators must use exposure profiles that reflect those encountered while foraging in the field, and must be exposed to these pesticides in a way that the pollinator would naturally encounter them.

Grey literature in the form of government reports from monitoring activities does not follow an experimental protocol and do not adhere to the above criteria. These reports received an automatic score of 100%, as they are often the most accurate representation we have for the status of some pollinators in Ontario. For example, OMAFRA provincial apiarist reports are the main documentation that conveys proportion of overwintering mortality and disease prevalence for honey bee colonies in Ontario.

A study that fulfilled all the above criteria would be assigned a score of 100% (7/7), whereas a study that fulfilled only three of the criteria would be assigned a score of 48% (3/7). Studies that receive a higher score are considered more robust and have more strongly weighted results compared to studies that receive a lower score.

### Literature Consensus

After the articles were collected and analyzed, we constructed consensus tables to visually represent the effect of each stressor on pollinator health in Ontario. Tables were constructed to include all studies that have been conducted in Ontario and Canada - to the best of our knowledge - in these areas. As our searches turned up very large numbers of articles, time constraints mean that we have only scored some articles from outside of Canada to represent the global perspective. The articles reporting research conducted outside of Canada were randomly selected from our reference library, with the assumption that they would provide a representative view of the impacts of stress factors from other countries.

The impact of each stressor on wild and managed bees is represented by a colour on the consensus tables. These colours follow a traffic light analogy, in that a green square indicates the factor has a positive effect on pollinators, according to the evidence base. A yellow colour indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory. Red colouration indicates the factor has a negative effect on pollinators.

The colour of the square is determined based on a simple mathematical formula:

$$\frac{\begin{array}{l} \text{proportion of studies showing a positive effect} \\ \text{proportion of studies showing a neutral effect} \\ + \text{proportion of studies showing a negative effect} \end{array}}{\text{overall effect of a stress factor}}$$

For example, one stress factor has four studies that examine its outcome on pollinators. Two studies found this stress factor has a negative effect on pollinators, one study shows a neutral effect, and one study shows a positive effect. The overall effect would be as follows:

$$\frac{(-2)}{4} + \frac{0}{4} + \frac{(+1)}{4} = \frac{(-1)}{4} = -0.25$$

The colour of each square on the consensus table would reflect the view that the evidence indicates this stress factor has a slightly negative overall effect on pollinator health. The overall effects are represented by the following colours on the consensus tables:

< -0.75 to -1.00	
< -0.50 but ≥ -0.75	
< -0.25 but ≥ -0.50	
< 0 but ≥ - 0.25	
0	
> 0 but ≤ 0.25	
> 0.25 but ≤ 0.50	
> 0.50 but ≤ 0.75	
> 0.75 to 1.00	

If there is no evidence for a stress factor on a particular pollinator, the square is assigned the colour grey. When reading the literature consensus, it is important to note three things: first, the colours of the cells. These colours indicate the directionality of effect on pollinators from each stress factor, and may give rise to notable patterns (i.e. some stress factors may elicit the same effect on all pollinators or it may have different effects on a per-species basis). Second, the grey cells in the consensus table represent knowledge gaps, where we do not yet know how a stress factor is influencing a pollinator group. These squares are arguably as important from a recommendations standpoint as the coloured squares, as research is needed to determine if and how these pollinators are affected by stress factors. In the absence of this research, we could be inadvertently affecting the health and populations of these pollinator species or groups. Third, it is important to note the numbers written in each cell. These numbers are the ‘quality scores’ for the studies determined as described above, and influence the degree of confidence we have in the evidence from which the overall effect of each stressor was determined. For example, a

dark red square with a quality score of ‘100’ tells us with confidence that a given stress factor negatively impacts the pollinator in question. A dark red score with the number ‘50’ tells us that this pollinator may be very negatively affected, but the studies supporting this would benefit from an increased level of scientific rigour.

### Functional Guild Diversity of Wild Bee Communities

Wild bees were divided into the following guilds for analysis: solitary ground nesters, social ground nesters, cavity nesters, bumble bees (except subgenus *Psithyrus*) and cleptoparasites (i.e. social parasites). Ground nesters were split into two guilds as social bee colonies can have many individuals per nest and are active over a much longer period of the year, whereas solitary bees have only one female per nest and are generally active for only a few weeks (Sheffield et al. 2013a; Williams et al. 2010).

#### **Solitary Ground Nesters**

These bees dig holes in the ground to nest in and live on their own instead of colonies: *Colletes*, *Andrena*, *Agapostemon*, *Lasioglossum* subgenus *Lasioglossum*, *Lasioglossum* subgenus *Dialictus* (other than the species listed under cavity nesters below; although many *Dialictus* are eusocial, those we found in this study are solitary (Gibbs 2010).

#### **Social Ground Nesters**

These bees generally prefer open habitats, often those with dry sandy soils: *Lasioglossum* subgenus *Evyllaesus*, *Augochlorella*, *Halictus*.

#### **Cavity Nesters**

These bees nest in pithy plant stems, rock cavities and abandoned beetle burrows in wood, usually using pre-existing cavities (Cane et al. 2007): *Hylaeus*, *Augochlora*, *L. (D.) cressonii* Robertson, *L. (D.) semicaeruleum* Cockerell, *Hoplitis*, *Osmia*, *Ceratina*.

#### ***Bombus* spp.**

These bees were placed in a guild on their own, as they are social cavity nesters (Goulson et al. 2008). Because species of *Bombus* subgenus *Psithyrus* are social parasites, the *Bombus* guild refers only to the non-parasitic species.

#### **Cleptoparasites**

*Sphecodes*, *Nomada* as well as social parasites *Bombus* in the subgenus *Psithyrus* were united under the guild “cleptoparasites” as they are all bees that lay their eggs in nests of other bee species. We did not break cleptoparasites up into multiple guilds based upon host nest site choice, because such ecological and life history data are not available for all species.

## STATUS AND TRENDS OF POLLINATORS IN ONTARIO

### Executive Summary

Pollinators are essential to agricultural production (particularly fruit, vegetable and nut crops) and maintaining the health and diversity of wild plant communities. There is well established evidence showing declines in pollinators around the world (reductions in species richness on a national/ landscape scale, range contractions of specific pollinator species, and reduced pollinator abundance) with associated evidence of reductions in pollination services leading to reduced crop yield (pollination deficits). This raises concerns for agricultural production and maintenance of biodiversity both for Ontario, Canada, and around the world.

Animals that provide pollination services are very diverse, including bees, flies, wasps, butterflies and moths, beetles and hummingbirds. Ontario is a Canadian pollinator biodiversity hotspot, containing 420 of 855 (49%) nationally recorded bee species – the highest bee diversity of any province. It is also the last province in which the formerly widespread Rusty patched bumble bee (*Bombus affinis*) was most recently found (a single individual was observed by Dr. Sheila Colla at the Pinery Provincial Park in 2009). As bees rely on flowers to provide all their food (nectar and pollen) they are typically the most important pollinators for the majority of plant species. Bees vary considerably in their ecology and life-history: the vast majority of species (810/855 or 95%) are solitary bees, while bumble bees (44/855 or 5%) and honey bees (1 species) form colonies of up to 65,000 individuals respectively. Two bee species (the western honey bee *Apis mellifera*, the bumble bee *Bombus impatiens*, are commercially reared and used as managed pollinators for agriculture in Ontario, while the remaining wild bees pollinate crops and wild flowers within flight range from their nest sites (e.g., undisturbed ground or cavities, such as dead wood).

This report highlights the major environmental stress factors likely to be affecting pollinator health in the province (land use change, climate change, agrochemical usage, pests & pathogens and management practices), assesses the strength of evidence supporting these trends, the likelihood of interactions between stress factors and identifies current knowledge gaps.

### Stress Factors Influencing Bee Declines

In recent decades, pollinator species worldwide have been dealing with the impacts of exposure to multiple, potentially interacting, and environmental stress factors. Several causal factors for global bee declines have been suggested, including long-term anthropogenic land use change (habitat loss, fragmentation and urbanization), climate change, pests and pathogens, invasive species, and the increasing use of agrochemicals (pesticides, herbicides, fungicides, etc.: Committee on the Status of Pollinators in North America 2007; González-Varo et al. 2013; Goulson et al. 2015; Potts et al. 2010; Vanbergen et al. 2013). The scientific community has started to build a well established consensus on how such environmental stress factors affect pollinator health; however, this task is made harder due to potential interactions between multiple stress factors.

Below we define each key stress factor that has been shown to influence pollinators. We discuss the nature of the effect and whether the evidence exists at the individual, colony (relevant for bumble bees and honey bees) and/or population levels.

## **Land Use Change**

Land use change is associated with an extensive variety of habitat transitions (Winfree et al. 2011). Human land use in recent decades has led to the alteration of most original wild pollinator habitats and landscapes through fragmentation, destruction and degradation (Kremen et al. 2007; Winfree et al. 2011). Land use change alters the availability and balance of food sources (flowers providing nectar and pollen) and nest sites, which are likely to be key limiting factors for wild pollinators.

## **Habitat Loss**

Habitat loss (via habitat degradation, destruction, and agricultural intensification) is thought to be the most important factor contributing to bee declines (Brown and Paxton 2009; Goulson et al. 2015; Vanbergen et al. 2013) and most likely all pollinators (Biesmeijer et al. 2006; Ollerton et al. 2014). The removal of original habitats directly and abruptly reduces (or eliminates) opportunities for forage and nesting sites (Steffan-Dewenter and Tscharrntke 1999). Rapid changes in ecosystems can result in reduced abundance and/or diversity, and changes in the overall composition of pollinator communities from what they were before the disturbance occurred (Steffan-Dewenter and Westphal 2008). When this change of habitat is from fields to urban developments or monoculture, it becomes difficult for these populations to recover.

## **Urbanization**

Urbanization transforms the landscape, bringing with it habitat loss and disturbance. Like most land use change, it can eliminate nest sites and native forage for pollinators. Urban areas are expanding throughout the world (UNPD 2006). Natural space becomes reduced and what exists is often in the form of simplified plant communities, or even monocultures (mowed lawns) that provide fewer food sources for most pollinator species. Tall buildings can reduce sunlight availability that may also interfere with dispersal, foraging, and orientation (Matteson and Langellotto 2010).

Despite the direct impacts on nesting sites and forage availability, urbanization does not appear to affect overall pollinator species richness or number of flower visits when urban areas are supplemented with some degree of floral resources (Baldock et al. 2015). Flower-rich green roofs are not limited by sunlight and can often provide important habitat for bees and butterflies (Colla et al. 2009; Matteson and Langellotto 2010). This habitat is less favourable than what can be found in non-urban areas as green roofs are isolated and fragmented habitats, but it is still some compensation for the habitat lost compared to a traditional roof offering no flowers.

## **Fragmentation**

Habitat fragmentation describes a patchy distribution of original habitats, resulting in an overall reduction in habitat patch size surrounded by regions of less hospitable or inadequate habitats for pollinators (Andren 1994). Consequently, it reduces the potential sizes of pollinator populations by increasing their isolation and transforming the landscape into less favourable environment. Isolated, fragmented habitats lead to loss of genetic diversity, which in turn increases the chances of inbreeding and extinction (Darvill et al. 2010; Dixo et al. 2009).



## Climate Change and Weather

Climate change refers to long-term changes in weather patterns (regional temperature, precipitation, extreme weather, etc.) in specific regions or globally. There is well established evidence that global warming (of about 0.6 °C over the past one hundred years) has negatively affected a wide range of organisms (Walther et al. 2002). In addition to the gradual warming of the planet, climate change brings extreme weather events (Coumou and Rahmstorf 2012). Both of these outcomes of climate change may impact pollinator health. Furthermore, climate change may have indirect negative effects for pollinators through their effects on pests and pathogens. Warming temperatures could expand the ranges of certain pests and increase the prevalence of pathogens (Le Conte and Navajas 2008).

### **Extreme Weather**

Extreme weather includes unusual, severe or unseasonal weather events. Extreme weather events that will accompany global warming may have severe impacts on pollinators already stressed by climate change. Less mobile pollinators, such as small beetles and ground nesting bees, may be the most severely impacted by events such as flooding. Extreme weather can negatively impact individuals by directly killing them in instances like this, but they can also negatively impact entire colonies or local populations. Unfavourable weather conditions may interrupt foraging and mating, lowering individual and (honey bee and bumble bee) colony fitness.

### **Phenology Shifts**

Climate warming is associated with phenological advances in a wide variety of organisms including plants and pollinators. Many plants are flowering earlier as a result of climate change causing earlier springs (Burkle et al. 2013). Consequently, pollinator species may undergo population declines if floral resources bloom at times when effective pollinators are unavailable, resulting in temporal plant-pollinator mismatches. Pollinators also require continuous availability of food resources during their flight period, and phenology shifts could lead to gaps in the succession of flowers causing a lack of food for longer-lived pollinators or colonies. The geographic ranges of pollinators themselves are also shifting as temperatures increase (Hoover and Hoover 2014). Bees that thrive in tropical environments are predicted to expand their ranges, whereas bees that thrive in narrow-ranged temperate climates will experience range reductions and risks to population declines.

## Agrochemicals

Agrochemical is a term derived from a contraction of “agricultural chemical”, and refers to the various chemical products used at all stages in agricultural systems. These include fertilizers, chemical growth agents (including hormones) and pesticides (including a broad range of insecticides, miticides, nematicides, herbicides and fungicides). There is well established evidence that agrochemicals, particularly pesticides, vary in their toxicity to pollinators (Arena and Sgolastra 2014; Blacqui re et al. 2012; Desneux et al. 2007; Godfray et al. 2014, 2015) and in most countries, including Canada; their use is highly regulated. Agricultural intensification has increased the use of agrochemicals around the world, resulting in habitat degradation and an increased risk of exposure to both managed and wild pollinators. Insecticides can cause mortality by direct toxic effects on pollinators (Alston et al. 2007) and exposure may result in local shifts in wild bee diversity and abundance (Brittain et al. 2010; Woodcock et al. 2016), whereas the impacts of herbicides

are more likely to affect pollinators indirectly by decreasing floral resource availability (de Snoo and Van der Poll 1989; Kleijn and Snoeijing 1997), but may also have direct toxic effects (e.g., Herbert et al. 2014; Morton and Moffett 1972). Miticides are commonly used treatments for parasitic mite control, particularly *Varroa* mites in managed honey bee colonies. However despite the use of these chemicals, honey bee colony numbers have continued to decline. Current risk assessments examining the potential impacts of agrochemicals on pollinators use ecotoxicological data from studies of honey bees as the sole insect pollinator species tested, even though the effects of pesticide exposure in particular varies substantially among species (Arena and Sgolastra 2014; Godfray et al. 2014, 2015; Nguyen et al. 2009). Finally, the effects of agrochemicals might not be restricted to agricultural lands because these compounds can move (via spray drift, or through movement of contaminated soil or water) into natural habitats where pollinators nest and forage (David et al. 2016; Krupke et al. 2012; Pisa et al. 2015; Potts et al. 2010).

### **Insecticides**

Insecticides are chemicals developed and used to kill insect pests. In addition to pests, they can harm non-target insects such as pollinators. In Ontario, neonicotinoids, organophosphates, pyrethroids and carbamates are commonly used insecticides (OMAFRA, 2014b). Neonicotinoids resemble nicotine in structure and bind to, and over stimulate, acetylcholine receptors in the insect's nervous system (Matsuda et al. 2001). There is considerable controversy surrounding the effect of neonicotinoids on pollinator health (e.g. Godfray et al. 2014, 2015; Lundin et al. 2015; Walters 2013). In recent years the impact of this class of pesticides (imidacloprid, thiamethoxam and clothianidin in particular) on non- target organisms has received considerable research attention around the world, as they are the most commonly used pesticides in the 21<sup>st</sup> century (Goulson 2013).

The enzyme acetylcholinesterase has been used as a biomarker for pesticide exposure, as several insecticides and herbicides bind to the neuronal acetylcholinesterase receptors, triggering a continuous signal that can cause nerve damage and death (Chandrasekara and Pathiratne 2007; Kavitha and Rao 2008; Xing et al. 2010). Neonicotinoids have a much greater binding affinity for acetylcholine receptors in insects compared to mammals (Tomizawa and Casida 2005). This makes them considerably more toxic to insects than mammals, a significant reason why they have been considered safer than other insecticides from the human safety perspective. Over stimulated nerve firing can cause death when neonicotinoid exposure levels are high, but at low levels they may also cause sublethal effects on physiology, behaviour and life-history (e.g. Desneux et al. 2007; Godfray et al. 2014, 2015; Pisa et al. 2015) In honey bees, many of the receptors that bind neonicotinoids are located in the mushroom body, a structure of the brain associated with learning and memory and is therefore crucial for foraging and colony communication (Palmer et al. 2013).

### **Fungicides**

Fungicides are among the most abundant and commonly used plant protection chemicals found in bees and bee/hive products (e.g. pollen, honey, wax) because they can be applied during bloom when bees are present (Mullin et al. 2010; vanEngelsdorp et al. 2009). Ideally, fungicides should have: 1) low mammalian toxicity, 2) low ecotoxicity, 3) low phytotoxicity, 4) high penetration rates for spores and mycelia, and 5) limited biodegradation on the plant surface (Phillips 2001). Most fungicides are applied as liquid (by spraying), but they can also be applied through injection, chemigation (irrigation),

ground treatment in furrow at planting and as seed treatments (often co-formulated with insecticides). Fungicides are a specific type of pesticide that control fungal diseases in plants by inhibiting or killing the fungus causing the disease. They vary considerably in their potential for causing adverse effects for non-target organisms, including pollinators. Some authors have reported fungicides are safe for adult bees (Atkins 1992), while other studies report harmful effects (Mussen et al. 2004). For example, chlorothalonil (Bravo) has been found in entombed pollen from honey bee colonies suffering from colony collapse disorder (vanEngelsdorp and Otis 2001a). Bravo has been reported as the most commonly detected fungicide in honey bees and their products (Mullin et al. 2010), and pyraclostrobin and boscalid (Pristine) can cause larval and pupal mortality in honey bees (Mussen 2008). Furthermore, concerns have been raised about interactive effects between sterol biosynthesis inhibiting (SBI) fungicides and pyrethroid insecticides in honey bees (Johnson et al. 2009; Pilling et al. 1995; Vandame and Belzunces 1998). Pristine and SBI fungicides are commonly used in Californian almond orchards, and have both been detected in pollen samples (Mullin et al. 2010; Mussen 2008). The likelihood of fungicide and insecticide co-application and/or co-occurrence on the same crop may increase the risk of combined exposure and potential for interactive (synergistic) toxicity effects on pollinators.

### **Herbicides**

Herbicides are commonly used pesticides that are designed to eliminate or suppress weeds in cropland (Boutin et al. 2012). Selective herbicides used in agricultural systems kill specific targets (weeds), and leave the desired crop plants relatively unharmed. They are the most commonly used pesticide on agricultural crops in Ontario (Statistics Canada 2006). The large number of herbicides are available for use in Ontario (Kozak 2013a), the geographic extent of their use on varying crops, and the quantity applied suggest a high probability that non-target organisms (including pollinators) are exposed (Boutin et al. 2012). Most herbicides are applied as sprays using ground equipment, but can also be applied aerially or through irrigation systems. Depending on the mode of application, the quantity of sprayed herbicides that ‘drift’ to adjacent areas can reach 1- 10% of the application rate within 10 m when using ground equipment and potentially much more with blower and aerial equipment (Boutin and Jobin 1998). It has been demonstrated that herbicides moving to off-target areas may affect sensitive non-target plants (de Snoo and Van der Poll 1989; Kleijn and Snoeijing 1997).

There are few recent studies assessing the toxicity of herbicides to bees. Johansen et al. (1983) report that herbicides are of little or no risk to bees, whereas Morton and Moffett (1972) report that phenoxy herbicides inhibited brood development in honey bees. Phenoxy herbicides are applied primarily as sprays and could be carried back to the colony if applied to floral sources on which honey bees forage. Most herbicides wilt flowers rapidly, and flowers which are not killed usually wilt, and nectar secretion can be inhibited. Krupke et al. (2012) detected atrazine and metolachlor on honey bees living near agricultural fields. These herbicides are commonly used in maize production however their toxicity to honey bees again is reported to be minimal (CFIA 2013). While some herbicides have been reported to directly affect honey bees by reducing brood development (Morton and Moffett 1972) and affecting learning performance (Herbert et al. 2014), the main impacts are perhaps more likely indirect by depriving pollinators of nectar and pollen sources from wild plants in treated areas.

## **Pest and Pathogen Treatments**

Chemicals that are used to control for pests and pathogens may also negatively affect honey bee health (Mullin et al. 2010). For example, hives can be exposed to miticides or organic acids to kill *Varroa* mites, and antibiotics or essential oils to treat bacterial infections. These compounds come into direct contact with honey bees and could create a tradeoff between attempting to kill pests and pathogens affecting bees without killing the bees themselves.

In addition to insecticides, herbicides, and fungicides, and pest treatments, other chemicals that honey bees may be exposed to in the environment are reviewed. These include exposure to *Bacillus thuringiensis*, bacteria used as an insecticide by either spraying on plants or genetically modifying plants to express the active bacterial gene, exposure to agricultural spray adjuvants and surfactants, other antibiotics outside of pathogen treatment, and heavy metals.

## **Pests and Pathogens**

A variety of pests and pathogens are known to cause problems for managed and wild pollinators. The best documented are those that affect honey bees, but viruses, fungi and parasites are also beginning to be uncovered in other managed and wild bees. Increasing human management of bees appears to be causing an adverse phenomenon called ‘pathogen spillover’. Managed bees may be the source of intense, diverse and novel infections due to regular contact in commercial production facilities and when used at high stocking densities in the greenhouse or field. When infected managed bees (or colonies) come into contact with wild bees, for instance when foraging on shared flowers, they may transmit these infections. Ultimately, pathogens ‘spilling over’ from managed to wild species could result in significant stress and declines in wild bee populations (Colla et al. 2006; Graystock et al. 2013; Murray et al. 2013). Pests affecting honey bees in Ontario are *Varroa* mites, tracheal mites, wax moths, and the small hive beetle. Pathogens include numerous species of bacteria, fungi and viruses. Bumble bees, especially managed *B. impatiens* colonies, are affected by viruses, the trypanosome parasite *Crithidia bombi*, tracheal mites, the fungal infection *Nosema bombi*, and small hive beetle *Aethina tumida*. The ALCB is susceptible to the fungal infection chalkbrood (although different to the one that affects honey bee colonies). Pests and pathogens targeting the BOB are not yet well studied. Below are brief descriptions and introductions of these pests and pathogens that affect bees.

## **Parasitic Mites**

### ***Varroa* Mites**

The single most destructive factor influencing winter mortality of honey bee colonies in Ontario is the ectoparasitic mite, *Varroa destructor* (Guzman-Novoa et al. 2010). This mite historically parasitized the Asian honey bee *Apis cerana*, but was first documented to appear on the western honey bee *A. mellifera* in the early 1960s (De Jong et al. 1982). Such a recent host switch causes *Varroa* to be highly pathogenic to *A. mellifera*, as these bees have not had time to acquire host-parasite adaptations to the same degree as their original *A. cerana* host. This pathogenicity is also due to several life history characteristics of *Varroa*. These mites parasitize and feed on the haemolymph of bees in all life stages including larvae, pupae, and adults. They reproduce in brood cells with bee larvae and each mite experiences 3-4 breeding cycles (Baker 2010). Mites are transferred between colonies by robbing workers (Frey et al. 2011) and importing infested bees by commercial

trade. The high degree of pathogenicity in combination with their ease of spread has facilitated *Varroa* to be found on every inhabited continent excluding Australia (Mutinelli 2014).

### **Tracheal Mites**

The respiratory system of honey bees is comprised of trachea, small tubes that carry oxygen to surrounding tissues. Tracheal mites, *Acarapis woodi*, reside in trachea and partially impair the respiration of bees (Harrison et al. 2001). During the summer months when bees live for a few weeks, tracheal mites only survive for one generation inside an individual bee. However, overwintering bees can live for several months, allowing many generations of mites to propagate and accumulate (Ochoa et al. 2005, Otis et al. 1988). This population rise in winter has led to tracheal mites becoming a causal factor in honey bee overwintering loss in the 1980's and 1990's (Eischen 1987; Otis and Scott-Dupree 1992) when their prevalence and infestation levels were higher than they are today (Ernesto Guzman-Novoa, pers. comm.). Colonies with tracheal mites tend to exhibit overt symptoms only when the infestation is severe. In these cases, bees appear lethargic, forage less, extend their wings outward, and crawl in front of the hive. Infested colonies also show reduced honey production (Eischen et al. 1989) and individuals have degenerated hypopharyngeal glands which may impair brood feeding (Liu et al. 1989). Similar to resistance in *Varroa*, increased grooming behaviour is the main characteristic in bees resistant to tracheal mites (Danka and Villa 2003), and these lines have been reared with success in Canada (vanEngelsdorp and Otis 2001b; OBA Tech-Transfer Program 2004), but maintaining resistance can be difficult.

### **Greater and Lesser Wax Moth**

The greater (*Galleria mellonella*) and lesser (*Achroia grisella*) wax moths are minor pests of honey bees. They inhabit beehives and consume honey, pollen, beeswax, and brood. Adult bees are effective in removing wax moth larvae, and so this pest is only a severe problem when hives are already weak (Ellis et al. 2013).

### **Small Hive Beetle**

The small hive beetle, *Aethina tumida*, is native to Africa and was first introduced to North America in 1996 (Neumann and Elzen 2004). Small hive beetles are active flyers and spread to colonies within the same apiary. They feed on honey, pollen, and brood. In Africa, they cause minimal problems and mainly help decomposition in abandoned or diseased colonies of the cape honey bee (Cuthbertson et al. 2013). However, European honey bees lack the aggression and means of eliminating escalating populations of small hive beetle from the hive shown by cape honey bees (Neumann and Elzen 2004). In North America, they infest colonies, causing bees to abscond, and then feed on remaining food sources and breed in the abandoned hives. There is established but incomplete evidence that small hive beetles are harmful for Western honey bees, as they experience reduced populations, brood area, and flight activity compared to infected African colonies and control colonies (Ellis et al. 2003). Limited evidence also suggests that there are no substantial interacting effects between small hive beetle and *Varroa* (Delaplane et al. 2010).

## Bacterial Diseases

### American Foulbrood

Two bacterial diseases that currently occur in Ontario are American foulbrood (AFB) and European foulbrood (EFB). American foulbrood is the most damaging bacterial disease that affects brood in honey bee colonies, and once contracted will usually result in colony death (Kozak 2012a). It is caused by the bacterium *Paenibacillus larvae*. The bacterial spores are resistant to antibiotics and disinfectant and can remain on contaminated hives and equipment for decades. If not destroyed, spores can spread to other colonies (Genersch 2010; Waite et al. 2003).

### European Foulbrood

European foulbrood is caused by the *Melissococcus plutonius* bacterium that infects brood, but is much less virulent than *P. larvae*. An otherwise healthy colony can survive European foulbrood infection, but stressed colonies have more difficulties fighting an infection. Severe infections are treated with oxytetracycline in Ontario.

## Fungal Diseases

### Chalkbrood

Chalkbrood is an infection caused by the fungus *Ascosphaera apis* in honey bees (Aronstein and Murray 2010) and *Ascosphaera aggregata* in alfalfa leafcutting bees (Goettel and Richards 1991). It exclusively targets brood and slowly feeds off of larvae and pupae as the fungus reproduces. Infection turns brood into black or white chalky ‘mummies’. These mummies are the defining characteristic of chalkbrood. Chalkbrood is a stress-related disease; several factors make larvae more susceptible to the disease, including chilling temperatures, weak colonies, moisture, poor ventilation and antibiotics abuse. Requeening is the main method used to treat chalkbrood in honey bees (Aronstein and Murray 2010). Removing mummies from nesting boards to reduce chalkbrood transmission is a common treatment in managed solitary bee species (James 2011).

### Nosema Species

Nosema disease is commonly regarded as a serious disease affecting adult honey bees. Nosema disease results from two species, *Nosema apis* and *Nosema ceranae*. These fungal species are genetically and morphologically similar and both reproduce in the midgut of honey bees. However, their respective symptoms and seasonal levels differ. *Nosema apis* is sometimes asymptomatic, but at other times can be identified by dysentery and adult depopulation. Its levels are highest in winter and spring and lowest in summer and fall (Copley et al. 2012). *Nosema ceranae* has no obvious symptoms and has been associated with adult depopulation, low honey production, abrupt colony death, and is highest in late spring and early summer (Fernandez et al. 2012, Traver et al. 2012). Nosema disease restrains the spring buildup of colony populations making them less productive units. Infected bees show a reduced pollination ability (Anderson and Giacon 1992) and produce less honey (Fries et al. 1984). They are also less able to find their way back to their hive after foraging trips (Dussaubat et al. 2013), have altered pheromone production (Dussaubat et al. 2010), and weakened immune systems making them more susceptible to other pathogens such as viruses (Antunez et al. 2009). At the colony level, brood production and population size are significantly lowered by infection with *Nosema* (Botías et al. 2013). Colonies infected by *Nosema* are usually treated with the antibiotic fumagillin.

## Parasites

### *Crithidia bombi* in Bumble Bees

*Crithidia bombi* is a well-documented trypanosome parasite infecting the digestive tract of bumble bees. These parasites are partially responsible for declining wild bumble bee populations. They cause bees to lose their ability to distinguish between beneficial and non-beneficial floral resources, ultimately causing starvation. Commercially bred colonies typically harbour higher levels of *C. bombi* than wild bees. It is believed that commercial bees that escape from greenhouses can transmit the parasite to wild populations, contributing to the spillover of this parasite.

## Viruses

Currently, nearly twenty species of viruses are known to infect honey bees, and among the most serious are sac brood, deformed wing virus, and acute and chronic bee paralysis virus (Kevan et al. 2006). Several of these viruses are beginning to be identified in other bees as well (Singh et al. 2010), but more evidence is needed to determine their prevalence and virulence in other species. There is considerable variation in the life stages of honey bees that are affected and the symptoms that result from these viruses. A list of viruses known to infect honey bees and their corresponding descriptions is shown in Table 4.

Historically, most viral infections were of minimal concern and had little to no effects on colony health until the introduction of *Varroa destructor* mites (Genersch and Aubert 2010). These mites are not only vectors for many viruses (as reviewed above), but they also activate asymptomatic viruses, causing serious health consequences that do not normally occur in absence of the mite (Grabensteiner and Nowotny 2001; Grzeda et al. 2014). The sudden collapse of seemingly healthy colonies has been attributed to this combination of *Varroa* mites and the viruses they transmit (Bakonyi et al. 2002). Similarly, viruses such as black queen cell virus (BQCV) can also be associated with and aggravated by *Nosema apis* (Anderson 1995), and deformed wing virus (DMV) is associated with small hive beetle (Eyer et al. 2009). Furthermore, other viruses such as DWV, acute bee paralysis virus (ABPV) and Kashmir bee virus (KBV) have been associated with cases of bee mortality (Ball and Bailey, 1997; Berthoud et al. 2010; Belzunces et al. 2010; de Miranda et al. 2010; Francis et al. 2013; Martin et al. 2012), and Israeli acute paralysis virus (IAPV) has also been related to colony collapse disorder (CCD: Cox-Foster et al. 2007).

## Management Practices

Management practices are an umbrella category that includes the methods or techniques people use to maintain optimal habitats and species. Management practices are often developed with the expectation that they will deliver a positive outcome, as is often the case, but sometimes the end result is unintentional stress on pollinators. For example, managing honey bees for monoculture pollination implies transporting bee hives to the field with the intention to benefit agriculture and maximize crop output (Aizen and Harder 2009). However, there may be unintentional stress placed on honey bees due to the travel (Simone-Finstrom et al. 2016). Additionally, sometimes beekeepers split their colonies too frequently and late in the season to rent more hives for pollination and these colonies may not have enough time to strengthen sufficiently to survive the winter. Similarly, chemical treatments are used to kill *Varroa* mites on the basis that honey bee colonies will be healthier without them, but there may also be health consequences to the bees from the use of these chemicals.

Management practices are often overlooked as a stress factor, but the close and intricate relationships humans have with managed bees results in our actions having direct effects on their health. For example, beekeeper management practices are a causal factor in honey bee overwintering losses in Ontario (Guzman-Novoa et al. 2010). Even wild bees -despite not being managed themselves – face outcomes from our management practices of the land and other species around them. How humans manage invasive species that may outcompete wild bees (Traveset and Richardson 2006), and how suitable habitat is restored to provide adequate foraging and nesting sites (Dixon 2009), all play a role in ecosystem health and sustainability.

### **Invasive Species Management**

Invasive species are any non-native species that are now found beyond their native range, have a negative effect on the environment or the health of pollinators, and have a tendency to spread. Invasive species can decrease pollinator diversity, particularly for specialist insects. Non-native insects may displace native pollinators through competition for natural resources and nesting sites (Barthell et al. 1998). Invasive plants could have a beneficial effect on pollinators by providing new nectar and pollen sources or they could be detrimental by outcompeting and replacing original food sources. Through these interactions, invasive plants can change insect communities at the population level (Bezemer et al. 2014). There are over 500 invasive plants in Ontario, and rarely do these species provide the food needed by native insects (UTRCA 2011). Lastly, invasive pests or pathogens can inhabit new hosts and directly cause morbidity and mortality in pollinators that have not yet evolved defences. For example, economic models estimate the introduction of invasive *Varroa* mites to Australia (a region they have not yet invaded) will cost \$16-39 million USD due to the health impacts for honey bees (Cook et al. 2007). How humans manage invasive species will affect future wild pollinator health.

### **Habitat Management**

Land management includes how humans manage agriculture (e.g., monoculture, tillage, mowing) and natural habitats (e.g., fire). Practices such as the development of large-scale monoculture crops may affect pollinators by reducing diversity and availability of forage and creating greater distances from natural and semi natural areas. Other practices, such as tillage, may be harmful or beneficial to some species of bees that nest in holes in the ground created by aerating the soil (Williams et al. 2010). Prescribed burns are a land management practice that can be beneficial to pollinators, as the practice eliminates ground litter and provides more nesting site substrates (Potts et al. 2003; Taylor and Catling 2011). Land management practices affect can affect pollinator species differently due to major differences in foraging range, nesting behaviour, and other life history strategies among taxa. It is therefore important to understand how land use practices impact each species (clade or guild) to determine how best to manage agricultural fields and natural habitats for pollinators and other organisms.

### **Restoration**

Restoration refers to human intervention that restores ecosystems and the natural habitats used by pollinators. In intensive agricultural landscapes, field edges restored with native perennial plants could enhance biodiversity and ecosystem services such as pollination by native pollinators. In fact, field edges restored with native perennial plants in the form of hedgerows have been shown to increase native bee abundance and diversity by providing food sources and well as nesting sites (Morandin and Kremen 2013a). Other restoration projects include the creation of pollinator parks and pictorial meadows in urban settings



(Baldock et al. 2015; Hicks et al. 2016), and the reclamation of landfills and industrial sites into meadow habitat (Rutgers-Kelly and Richards 2013). As long as all functional pollinator groups are retained and seed set is occurring, then pollinator habitat could be considered to have been functionally restored (Forup and Memmott 2005).

### **Bee Management**

Bee management includes how the honey bee colonies are managed by humans, including transportation, supplemental feeding, overwintering conditions, treatments for pests and pathogens, and bee breeding. Humans have domesticated honey bees and selectively bred them to exhibit a variety of desirable traits including docility, increased honey production, and hygienic behaviour. Domesticated bees that are managed globally are therefore genetically different from their unmanaged progenitors (Harpur et al. 2012). Managing bees has introduced them to a variety of other stressors they may not normally experience as wild bees in their native habitats – stresses like new diseases and cross-country transportation (vanEngelsdorp and Meixner 2010). Management practices have been adopted to keep bees as healthy and productive as possible to be used for honey production and crop pollination. Some examples of these practices include manipulating their overwintering conditions (e.g., in climate controlled sheds), treating them for pests and pathogens, and supplementing them with food. All these practices taken together influence honey bees. Recently, three other bee species have begun to be managed in Ontario including *B. impatiens*.

### **Summary of Evidence**

The results of our extensive literature search strongly suggest that land use changes resulting in loss or fragmentation of suitable habitat are associated with negative impacts on wild pollinators. Evidence for managed pollinators was more limited, perhaps because these bees are less closely associated with the locations in which they are placed. Urban landscapes are able to support an appreciable diversity of wild bees, but the establishment of new urban developments (involving significant changes in land use away from suitable habitat) is unlikely to have a beneficial impact on pollinator health. We found well established evidence of detrimental effects of agricultural intensification on wild pollinator species.

There is limited evidence supporting the influence of climate change on pollinators in Ontario. However, relevant studies from around the world have shown climate change is one of the leading causal factors affecting wild pollinator populations. Butterflies are the most intensively studied pollinator group with respect to climate change, and they show appreciable advancements in their annual emergence time, northwards range shifts and movement towards the top of mountain ranges. The extent to which climate change will disrupt or maintain the existing plant-pollinator mutualisms in the face of such directional timing shifts appears to depend on the region where work was conducted and the species studied.

There has been significant research activity to examine the impacts of agrochemicals on pollinators in Ontario, with the majority of these studies considering the effects of pesticides on honey bees. The impacts of synthetic miticides and alternative pathogen treatments, particularly those used to control *Varroa* mites, have been widely studied in the province. Many of these chemicals show toxic effects for honey bees (as well as mites), which can be significantly affected by the timing and methods of treatment application. Despite the widespread use of fungicides and herbicides in agriculture there is

limited evidence from research in Ontario, Canada or around the world on the effects of these agrochemicals on honey bees, other managed pollinators or wild bees. There is conflicting evidence for the impacts of neonicotinoid insecticides on honey bee health from Ontario, but there is established but incomplete evidence that they have negative impacts on other managed bee species (PMRA, 2014). The evidence base on insecticide impacts from Ontario is strengthened considerably by established but incomplete evidence of negative effects on pollinators from studies conducted in the rest of the world.

There is well established support for the impacts of pests and pathogens for managed pollinators, particularly the honey bee. Evidence for similar impacts of pests and pathogens on wild pollinators is established but incomplete, but this evidence is based on very few studies at present. *Varroa* mites, and associated viral infections, remain a major threat to honey bees and small hive beetle (*Aethina tumida*) is an emerging problem in Ontario. Bacterial and fungal diseases, and viruses are reoccurring issues faced by beekeepers and other users of managed pollinators. In the absence of widespread pest and pathogen monitoring it is hard to characterize the extent of these stresses for managed or wild pollinators in Ontario. Pathogen spillover among pollinator species is emerging as a potentially significant threat, already reported for small hive beetle, tracheal mites, *Nosema* and several viruses. In the absence of appropriate infection monitoring and control this could be problematic for pathogen spread between managed pollinators, and also from managed to wild species. There is limited evidence showing interactive effects between pathogen infection and insecticide exposure for honey bee and bumble bee health from Europe and the USA, but nothing is currently known about this from published studies conducted in Ontario.

There is well established evidence that restoring native flower patches close to agricultural land increases both managed and wild pollinator abundance, and likely the crop pollination services they provide. There is conflicting evidence from field and laboratory studies that monoculture negatively affects honey bees, where the outcome depends on the crop used and the initial health status of the bees. Transporting bees to monoculture fields using migratory beekeeping practices is emerging as a significant source of honey bee colony stress. Supplementing hives with pollen and sugar syrup can be beneficial for honey bee health, but the effect depends on the nutritional quality of supplements used. There is established but incomplete evidence on storage and disease management practices to promote overwinter survival and crop pollination with non-*Apis* managed pollinators. The impacts of invasive pests and pathogen species can be very significant, e.g. *Varroa* mites and small hive beetle (*Aethina tumida*) for honey bees. There is conflicting evidence for the impacts of invasive species on pollinators and the crop pollination services they provide, depending strongly on the ecology and life-history of the invasive species and the plant-pollinator community it affects. There is well established global evidence indicating that examining changes in functional guilds provides a deeper understanding of how pollinator communities respond to management practices.

## Suggestions

- Pollinator declines result from the interacting impacts of several environmental stressors, including land use change, climate change, agrochemical usage, pests and pathogens and management practices.
- Mitigating, and reversing, pollinator declines requires us to ameliorate the impacts of these environmental stressors. Research to understand the severity of interactions among multiple stressors will help us develop a more coherent and effective set of mitigation strategies.
- Managed pollinators are not a substitute for wild pollinators in agricultural crop production. They should be considered as enhancements to the ‘free’ services of wild pollinators.
- The availability of food (flowers) and nesting sites are limiting factors for wild and managed pollinators. Creating new habitat, and enhancing existing land areas, to enhance pollinator resources can have positive impacts: whether enhancing urban gardens and parks, field margins and marginal land on farms, and headlands or land alongside roadways, railways or power lines.
- Habitat creation and management needs to consider the diversity of pollinators and their needs to ensure resources are appropriate. For example, considering the timing and duration of flowering compared to pollinator lifecycles, and the spatial distribution of food and nest sites in the landscape to enhance and maintain connected pollinator populations. These will also depend on landscape context, for example comparing urban cityscapes with provincial parks.
- Habitat creation and management requires buy-in from all stakeholders working together to find sustainable and affordable solutions. Land management to enhance pollinators is compatible with enhancing other ecosystem services: including habitat provision for natural enemies by other beneficial arthropods to enhance bio-control of crop pests and seed dispersal by birds.
- Long term monitoring programs have a key role to play: monitoring diversity and distribution of both managed and wild pollinators, their pest and pathogen levels and agrochemical exposure will provide us with status and trends across the province over time, allowing us to prioritize regions and/or habitat types of concern, and mechanisms to assess the effectiveness of strategies implemented to enhance pollinator health.
- Education for beekeepers regarding appropriate strategies for varroa monitoring and management, including the use of natural compounds (e.g. essential oils), is critical to improve honey bee colony health in the province.
- Honey bee colony health would also be improved by additional research on breeding for varroa tolerance and resistance.
- Research is needed to address essential knowledge gaps (grey cells, Figure 7) and establish best practices to ameliorate known stressors (red cells, Figure 7) and enhance positive impacts (green cells, Figure 7).

## **LAND USE CHANGE**

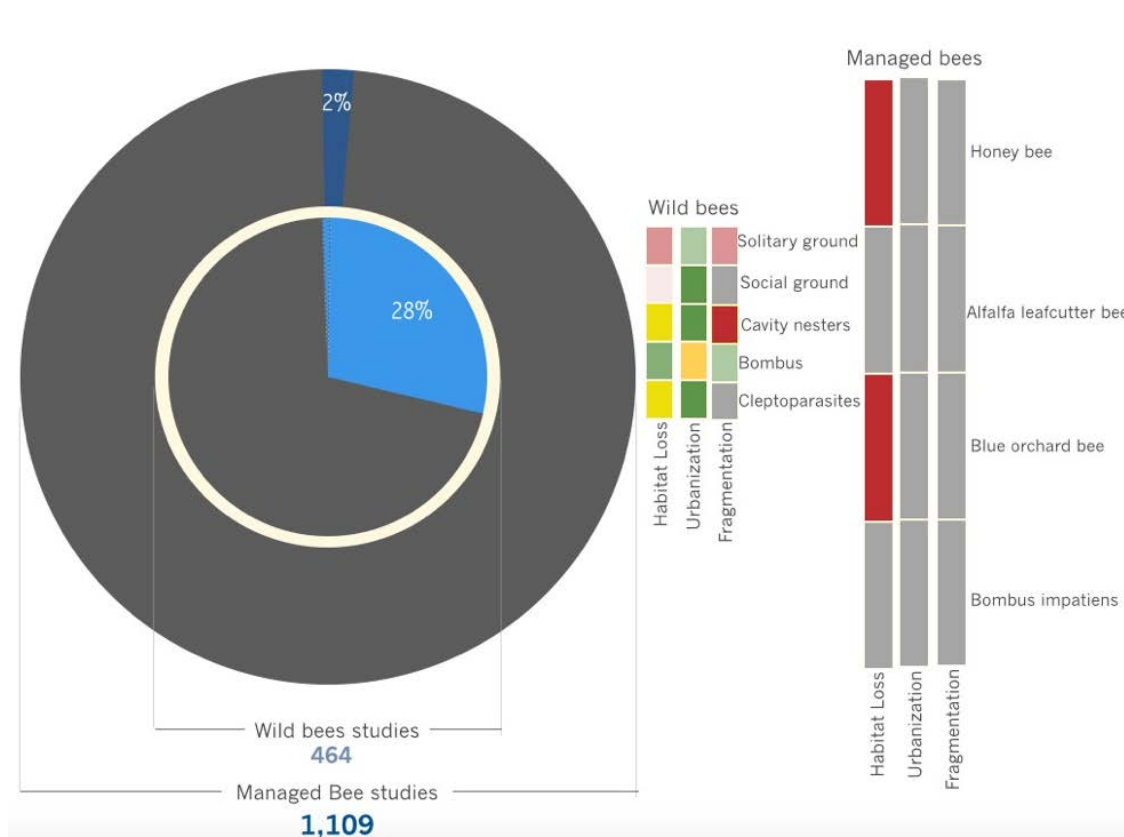
The loss and fragmentation of natural and semi-natural habitats has been widely identified as a primary cause of pollinator decline (Goulson et al. 2008; Kearns et al. 1998; Rathcke and Jules 1993). Specifically, land use change from agricultural intensification can alter the landscape extent and quality of habitats that provide food and nesting resources for pollinators (Kremen et al. 2007; Roulston and Goodell 2011; Vanbergen 2014). In recent years, ecologists have started to identify key population, life history and ecological attributes that influence how species respond to land use changes such as habitat loss, urbanization, fragmentation, and agricultural intensification (Davila et al. 2012; Vanbergen 2014; Williams et al. 2010).

For many pollinators, environmental change seems to affect species differently, causing declines in some species and populations, while others respond positively in human-altered landscapes (McKinney and Lockwood 1999; MacIvor and Packer 2016). The consequences of landscape alteration and habitat modification on pollinators have direct implications for plant mating systems, plant population persistence and community dynamics (Vanbergen 2014; Winfree 2010). For example, urban land has been rapidly expanding worldwide and the proportion of people living in urban areas has crossed the 50% threshold (UNFPA 2007). However, studies have suggested that urban landscapes have the potential to host relatively diverse and intact pollinator communities (Baldock et al. 2015; Le Feon et al. 2010; MacIvor et al. 2014).

Wild bees vary in multiple ecological and life history traits (Williams et al. 2010). Their responses to land use change and disturbance are likely to depend on traits that determine species mobility, physiological tolerance, and access to requirements for nesting and forage sites (Williams et al. 2010). Traits including body size, nest location, nest construction, degree of sociality, dietary specialization and activity periods appear to affect responses to impacts in land use. It is expected that traits that commonly determine species' response to disturbance will result in not only species loss following the disturbance, but will also result in specific shifts in community and guild composition reflected by our consensus tables and discussed below.

### **Summary of Evidence**

Overall, responses to landscape changes are predominately negative, but are highly variable within and across pollinator taxa (Niemela et al. 2000; Williams et al. 2010; Winfree et al. 2011). There is significantly more evidence on the impacts of land use change on wild compared to managed pollinators. We found no evidence on the effects of urbanization and/or fragmentation on managed pollinators in Ontario, and limited evidence of these impacts on wild pollinators. There is however, well established evidence from the USA and Europe on the effects of habitat loss on pollinators. Many studies have also shown that diversity and/or abundance of specialist wild pollinator species, decreases with all land use changes (Figure 7). In addition, wild pollinator species are to some degree compatible with urban landscapes, this seems especially true for ground-nesting bee species. There is also well established evidence showing detrimental effects of agricultural intensification on wild pollinator species.



**Figure 7.** Pie chart illustrating the percentage of unique relevant studies that investigated the impacts of land use change on both wild (light blue sector, inner circle) and managed bees (dark blue sector, outer ring). The literature consensus tables, shown on the right side of this figure, demonstrate the impacts of land use change on wild and managed bees. Green indicates the factor has a positive effect on pollinators, yellow indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory, and red indicates the factor has a negative effect on pollinators. Grey cells in the consensus table represent current knowledge gaps (for more details see page 20).

## Managed Pollinators

### Habitat Loss

Very few studies have examined the impacts of land use change on managed pollinators. This is concerning since many view land use change to be one of the leading causes of pollinator declines around the world (Biesmeijer 2012; Dicks et al. 2015; Kremen et al. 2007). We were unable to find any studies that specifically investigated the effects of habitat fragmentation, urbanization or agricultural intensification on managed pollinators in Ontario. However, our search did uncover one scientific note indicating that foraging patterns of honey bees differed in Southern Ontario depending on availability of foraging resources (Stimec et al. 1997).

There is some established evidence from the USA and Europe showing that areas of open land have a significantly higher honey yield per colony (Couvillon et al. 2014a;

Donkersley et al. 2014; Naug 2009; Otto et al. 2016; Steffan-Dewenter and Kuhn 2003). That is, the more natural or semi-natural habitat available for managed honey bees, the more food resources are available to them. In addition, studies from the UK have shown that honey bees will communicate with each other to specify which areas provide more abundant and/or higher quality foraging resources (Couvillon and Ratnieks 2015; Couvillon et al. 2014a, 2014b).

We also found evidence from the USA and Europe demonstrating negative impacts of land use change on the managed species *O. lignara* (BOB) and *M. rotundata* (ALCB)(Hinnert et al. 2012; Williams and Tepedino 2003; Williams and Kremen 2007). These studies have shown the distribution of floral resources and potential nesting sites across habitats influence species resilience in habitats (Amaya-Marquez et al. 2008; Kraemer and Favi 2005; Zurbuchen et al. 2010a). Overall, the ability of species to move among habitats to obtain floral (and to a lesser extent nesting) resources plays a critical role in driving the presence of species in various habitat types.

### Wild Pollinators

#### **Habitat Loss and Agricultural Intensification**

We found speculative and competing evidence from Ontario that examined the effects of habitat loss through agricultural intensification on wild pollinator health. One study, using a large dataset of bumble bee occurrence records and agricultural census data, found that pesticide use and habitat loss are unlikely to be major causes of decline for any of the *Bombus* species examined (Szabo et al. 2012). A substantial body of well established evidence from other countries suggests that wild bee declines are driven by changes in agricultural policy and practices, especially over the last 20 years with widespread and rapid agricultural intensification (e.g. Benjamin et al. 2014; Cariveau et al. 2013; Chamberlain et al. 2013; Gathmann and Tschardt 2002; Kim et al. 2006; Marini et al. 2012). In Canada (including Ontario), agricultural practices have changed significantly over the last two decades with consolidation of land into fewer, much larger farms. Farm numbers have dwindled by 26.5% from 280,043 in 1991 to 205,730 by 2011. Over the same 20-year period, the average farm area increased by 30%, from 598 to 778 acres (Statistics Canada 2012b).

Several studies have been completed in other Canadian provinces investigating the impacts of habitat loss on wild bees (Chamberlain et al. 2013; Cutler et al. 2015; Marini et al. 2012, Morandin and Winston 2006; Scott-Dupree and Winston 1987; Sheffield et al. 2008b; Sheffield et al. 2013a, 2013b). These studies show strong negative impacts on wild bees from habitat loss as a result of agricultural intensification. Collectively, Sheffield et al. (2013a, 2013b) showed that across a range of agricultural intensification, bee diversity was lower in the intensely managed apple orchards compared to old fields within the Annapolis Valley, Nova Scotia. With some exceptions (Chamberlain et al. 2013), higher wild bee species richness was observed in crop fields with natural or semi-natural land in close proximity compared to fields without natural land nearby (Cutler et al. 2015; Sheffield et al. 2008b).

There is also well established evidence from the USA indicating negative impacts of habitat loss and agricultural intensification on wild bees. For example, Grixti et al. (2009) found that major bumble bee declines in the American Northwest coincided with agricultural intensification. Several other studies also show consistent negative impacts

associated with agricultural intensification (Cariveau et al. 2013; Kim et al. 2006; Koh et al. 2016; Kremen et al. 2002a, 2004), and conclude that solitary bees appear even more sensitive than bumble bees to such land-use changes (Kremen et al. 2015). Wild bees are especially sensitive to agricultural intensification, as they often require below ground nest sites and sufficient food plants for nectar and pollen in close proximity to nesting sites. Abundance and diversity of wild bees are often lower on crops, especially expansive monoculture crops, than on the surrounding vegetation (Kremen et al. 2004; Morandin and Kremen 2013b) or even at field margins (Cutler et al 2015). Solitary bees may be more affected than bumble bees for multiple reasons: firstly, many solitary bees are specialists often having more specific floral requirements (particularly for pollen) than bumble bees (Michener 2004) and can therefore be directly impacted by decreases in floral diversity such as that provided in monoculture crop systems. Secondly, larger bodied species, like bumble bees, exhibit longer foraging distances than smaller (solitary) bee species (Benjamin et al. 2014; Gathmann and Tscharrntke 2002; Greenleaf and Winfree 2007).

A meta-analysis by Ricketts et al. (2008), found that yield declined due to shortage of pollinators with increasing distances between the crop and natural or semi-natural habitats. In large, intensively managed fields there are proportionately fewer field margins and hedgerows to provide nesting habitats and sufficient floral resources for wild bees and other pollinators. In addition, several studies have also found that wild bee diversity, visitation rate, and fruit set were enhanced in crops near natural areas as opposed to fields further away (Klein et al. 2003; Kremen et al. 2002b; Ricketts 2004). Bees are central-place foragers, meaning that they return to fixed nest sites after foraging (Schoener 1979). Thus, their proximity to natural habitats is critical for crops relying on bee pollination services.

In Europe, where it is estimated that only 15% of land area remains unmodified by human activities (Primack 2006), Biesmeijer et al. (2006) compared pre-1980 bee and hoverfly communities to post-1980 communities using a 10x10km cell grid system and found significant declines in bee and hoverfly species richness. Species that increased post-1980 tended to be common pre-1980, whereas species susceptible to decline tended to have specialist diets, long-tongues, and characterized by slower development and lower mobility (Biesmeijer et al. 2006).

Evidence from Europe was generally in accordance with evidence from North America. For example, several European studies also revealed that crop pollination services decline with increasing distance from natural habitats as a result of agricultural intensification (Bartomeus et al. 2014; Gonthier et al. 2014). However, in contrast to the USA, studies from Europe have been completed over larger geographical areas and over longer periods of time. For instance, Le Feon et al. (2010) completed a large-scale study in four European countries that demonstrated negative effects of agricultural intensification on species richness, abundance and diversity of wild bee communities. The study used a well-replicated design to investigate the effects of agricultural intensification across landscapes and found that species richness, abundance and diversity of wild bees were greater in sites turned towards crop production compared to sites with intensive animal husbandry. Furthermore, using an extensive FAO dataset of annual data for 1961-2006, Aizen et al. (2009) showed a significant pollination deficit in 87 important crops, suggesting there are too few pollinators to achieve maximum yield in these crops. Aizen et al. (2009) also clearly demonstrated that global agriculture has become increasingly pollinator dependent over time and the demand for agricultural land has rapidly intensified.

## Urbanization

We found limited evidence from Ontario on the impacts of urbanization on wild pollinators. Horn (2010) found that abundance and diversity of bees did not vary based on land use in cities. However, both abundance and diversity were higher at specific sites with naturalized areas. These results suggest that urban landscapes have the potential to host relatively diverse and intact bee communities. In 2011, 86% of Ontario's population resided in urbanized centres (Statistics Canada 2011) and it is relatively unknown how different landscapes, such as urban landscapes, influence foraging decisions. MacIvor et al. (2014) examined the type and diversity of pollen collected by two solitary bees (a native and an exotic) common in Toronto. The study reported that dominant pollen in brood cells were either a widespread, lawn-invasive plant species (*Trifolium repens*) or one of two wind-pollinated tree genera (*Quercus* and *Betula* spp.). There was also significant overlap in the pollen collected by both solitary species, however the exotic was slightly more specialized than the wild species. Another study by MacIvor and Packer (2015) demonstrated that 'bee hotels' (artificial nest sites for cavity nesting solitary bees) – a tool used for wild pollinator conservation – might not in fact have a positive effect for pollinator conservation. The study showed that wild wasps were significantly more abundant than both wild and introduced bees and highlighted the need for more research on the impact of bee hotels in pollinator conservation.

In contrast to research in Canada, there is well established evidence from the USA on the positive effects of urbanization on wild pollinators (Carper et al. 2014; Matteson and Langellotto 2010; Matteson et al. 2013; McFrederick and LeBuhn 2006; Wojcik and McBride 2012). For example, Fetridge et al. (2008) surveyed 21 residential gardens in a suburban area within close proximity to New York City. Their samples documented 110 bee species, of which 95% were wild, 50% were solitary and 93% were polylectic (feeding generalists). Fetridge et al. (2008) found that urban gardens supported considerable bee species diversity and richness, and were not devoid of ground nesters. Instead they found that bee communities resembled those of a forested research preserve located in the same region, although notably, certain specialists and forested-associated species were absent. These results are also in accordance with several other studies that found suburban and urban development hosted as many bee species as natural and semi-natural fragments (Kearns and Oliveras 2009; Larson et al. 2014; Lowenstein et al. 2014; Matteson and Langellotto 2011; Williams and Winfree 2013).

There is also well established evidence from Europe of the impacts of urbanization on wild pollinators. However, evidence from Europe generally illustrated negative impacts along gradients of urbanization (Ahrne et al. 2009; Banaszak-Cibicka and Zmihorski 2012; Bates et al. 2011; Fortel et al. 2014; Geslin et al. 2013). For example, Fortel et al. (2014) demonstrated changes in the abundance, species richness, and composition of wild bee community along an urbanization gradient. Habitats with an intermediate level of urbanization were found to contain the greatest number of species. Urbanization typically alters species composition from that of the surrounding landscape (Grimm et al. 2008; Matteson et al. 2008) and decreases biodiversity as it encroaches on rural habitats by bringing habitat disturbance and loss, consequently reducing nest sites and native forage availability. However pollinators, specifically bees, are to some degree compatible with urbanization and are able to exist in urban landscapes in diverse assemblages (Bates et al. 2011; Fetridge et al. 2008; Geslin et al. 2013). Urban communities can provide considerable plant species richness, often over longer time periods than more natural environments, with the establishment of parks and urban gardens (Benvenuti 2014). In



addition, anthropogenic structures may provide nest sites for a variety of pollinator species, especially cavity nesters (MacIvor and Packer 2015). When interpreted this way, it is not surprising that there is considerable evidence that urban environments can have positive effects on many of the functional guilds, particularly cavity nesters. Using flower-visitation networks from 36 sites in three landscapes (urban, farmland and nature reserves), Baldock et al. (2015) showed that pollinator abundance and species richness did not differ significantly between landscapes, however, bee richness was higher in urban sites compared to farmland.

### **Fragmentation**

Studies that have investigated the impacts of habitat fragmentation have shown it can reduce the size of populations, increase their isolation, and transform the landscape into a new environment such as agricultural fields or urban centres (Rathcke and Jules 1993). Habitat fragmentation can disrupt wild bee populations by reducing pollinator abundance and diversity and consequently reducing seed set in flowering plant species (Rathcke and Jules 1993).

There is limited evidence from Canada on the effects of habitat fragmentation. Using bee data collected from 19 different oak savannah remnants, Wray et al. (2014) found no differences in wild bee richness and abundance from oak savannah remnants, but there were distinct differences in plant and bee community composition between habitat types (forest and urban areas). Specifically, the authors found that urban oak savannah fragments had a greater density and richness of early-flowering wild plant species, and supported a greater abundance of large bodied bee species compared to other habitat types. Another study found that floral and nesting resources in urban and forest oak-savannah fragments greatly influenced bee community composition (Wray and Elle 2015).

In a meta-analysis of bee responses to disturbance, Winfree et al. (2009) found that wild bee abundance and diversity were significantly negatively affected by disturbance, particularly habitat fragmentation. However, contrasting findings from other studies from the USA have shown that fragmented habitat can have positive impacts on wild bee diversity (Brosi et al. 2007; Ricketts 2004; Russell et al. 2005; Williams and Kremen 2007). For example, Russell et al. (2005), found that fragmented power line corridors support higher bee diversity. This study also emphasized that surrounding habitat has a strong influence on the bee species found within fragments, as some bees may be foraging in the power line corridors but nesting elsewhere. Decreasing habitat patch size, as a result of fragmentation, can result in reduced species richness (Krauss et al. 2009) and significant shifts in the wild bee community (Bommarco et al. 2010; Brosi et al. 2007). Therefore, habitat patch size plays a significant role in determining whether effects of fragmentation are positive or negative for wild pollinators (Cane 2001). In addition, there is also evidence that generalist pollinators may be less vulnerable to fragmentation than specialists (Rathcke and Jules 1993) as they often exist in widespread populations.

In Europe, numerous studies have investigated the impact of habitat fragmentation on wild pollinator species richness and abundance (Goulson et al. 2010; Murray et al. 2012; Steffan-Dewenter and Tscharntke 1999; Steffan-Dewenter et al. 2001, 2002). Overall, European findings support studies from North America and show that habitat patch size plays a big role in determining effects of fragmentation (Carvalheiro et al. 2012; Dormann et al. 2007; Hinnert et al. 2012). Several studies have indicated that pollinator declines from habitat fragmentation have cascading effects on ecosystems because pollinator

species richness and abundance seriously alter the balance of plant-pollinator mutualisms (Hoffmann and Kwak 2007; Steffan-Dewenter et al. 2001). This can lead to further reductions in both gene flow and re-colonization rates in fragmented habitats for both pollinators and plants alike (González-Varo et al. 2009; Hoffmann and Kwak 2007).

### Suggestions

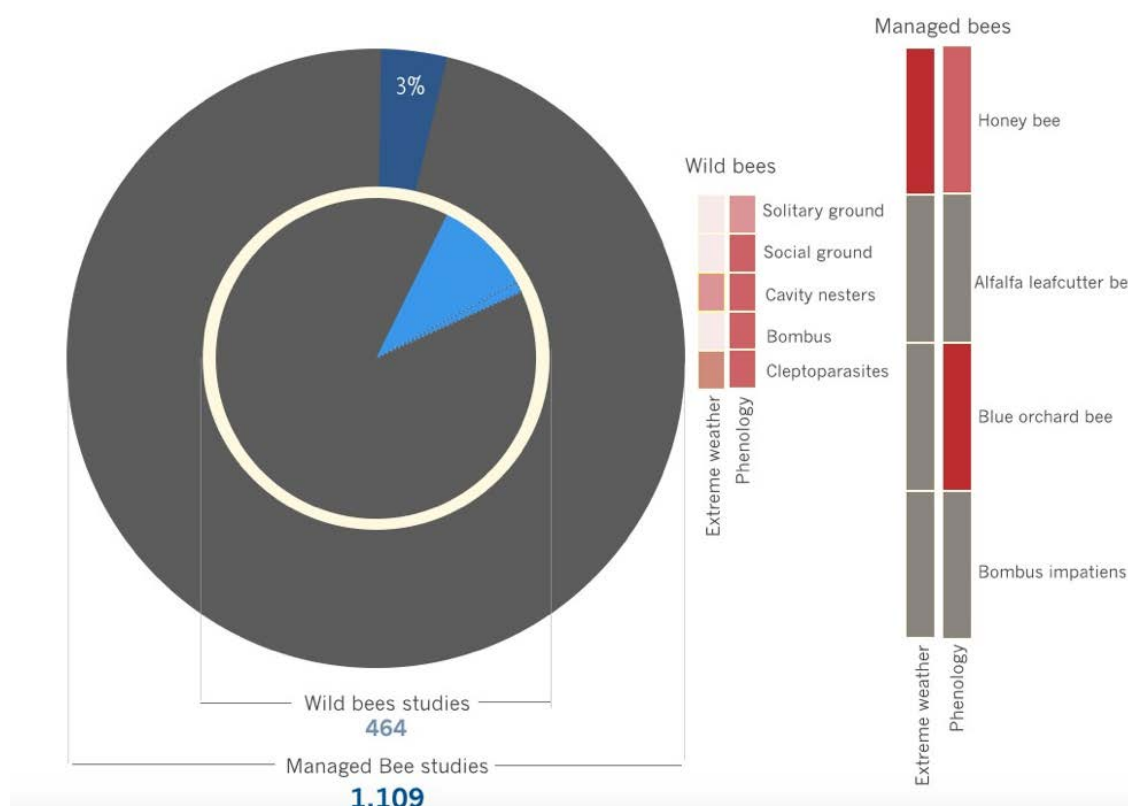
- Future directions for the field of land-use change impacts on pollinator ecology would involve analysis of functional guild responses to land use classifications. This could be achieved using existing sampling data and correlating taxon specific responses to habitat classifications on a GIS platform.
- To date, no research has been conducted on honey bees, wasps, flies, beetles and hummingbirds to investigate their responses to habitat loss, urbanization and fragmentation.
- Another approach would be to examine urban bee community dynamics, and employ manipulative studies to determine relationships between bee habitat use and significant habitat characteristics. In particular, the abundance of cavity nesting species in urban environments raises several questions. Firstly, are cavity-nesters increasing in urban areas as a result of manmade nesting sites? Secondly, are the diversity and abundance of cavity-nesting bees in urban areas reaching levels higher than those documented in surrounding natural habitat?
- A general lack of knowledge regarding bee nesting, especially in anthropogenic environments, highlights the need for future research on this aspect of bee ecology.
- Finally, we suggest there is a significant need to evaluate the pollination services provided by wild bees to Ontario crops, and to include the economic and non-monetary value they provide to agriculture in policy-making decisions.

### CLIMATE CHANGE

Given the world's climate is steadily warming, it is essential to document and attempt to predict the impacts climate change will have on species (Parmesan and Yohe 2003). Anthropogenic climate change is thought to have been occurring around the world since 1974 (Parmesan and Yohe 2003). Many studies have identified climate change as the most critical and damaging threat to pollinators in the 21<sup>st</sup> century (Abrol 2012b; Burkle and Alarcon 2011; Forrest and Miller-Rushing 2010; Prather et al. 2013; Williams and Osborne 2009), however the evidence in Canada, including Ontario, is generally lacking.

Climate-related factors such as seasonal temperature extremes are known to strongly affect species' geographical and thermal range limits (Devictor et al. 2008; Parmesan et al. 2011). Studies have shown many animals have been predicted to exhibit northern displacement in response to global climate changes to cope with rising temperatures (Currie et al. 2004; Parmesan et al. 2011; Pellissier et al. 2013). However, in many cases the pace of climate change surpasses many species' abilities to disperse into safe environments (Devictor et al. 2008). Understanding the capacity for which species are able to survive changing climatic conditions is imperative, particularly for species that are less mobile (Abrol 2012b). Many animal species appear to have already reached their geographical and thermal safety limits (Huey et al. 2009), and surpassing these limits substantially raises the risks of species extinction past critical (Araújo et al. 2013; Sunday et al. 2014).

Phenological shifts have been among the most obvious and thoroughly documented biological responses to the climate warming (Bartomeus et al. 2011; Forrest and Thomson 2011; Memmott et al. 2007; Polce et al. 2014). Many phenological events of species such as reproduction and emergence arise from complex interactions among the species and environmental factors. Therefore, having a deeper understanding of how environmental factors such as extreme temperatures and weather events affect species may help alleviate species' immediate risk of extinction.



**Figure 8.** Pie chart illustrating the percentage of unique relevant studies that investigated the impacts of climate change on both wild (light blue sector, inner circle) and managed bees (dark blue sector, outer ring). The literature consensus tables, shown on the right side of this figure, demonstrate the impacts of climate change on wild and managed bees. Green indicates the factor has a positive effect on pollinators, yellow indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory, and red indicates the factor has a negative effect on pollinators. Grey cells in the consensus table represent current knowledge gaps (for more details see page 20).

### Summary of Evidence

Significantly more established evidence is found from Europe than North America and shows climate change is one of the leading causal factors for impacting pollinator populations (Figure 8) (e.g., Franzen and Ockinger 2012; Lavergne et al. 2010; Polce et al. 2013; Williams 2005). Our literature search resulted in limited evidence on the influence climate change may have on pollinators in Ontario (Skandalis et al. 2011; Williams et al.

2009). There is considerably more evidence on the impacts of climate change on native compared to managed pollinators. Studies have suggested that the greatest impact climate change is having on pollinators is advancement of their rate of emergence. In some studies the rate of emergence has advanced by 10 days over several years. Very few studies have examined distributional shifts in wild pollinators other than butterflies. Studies investigating impacts of climate change on butterflies have shown that many species have exhibited northern range shifts, along with movement of species up mountain ranges to cooler climates (Bedford et al. 2012; Kharouba et al. 2009; White and Kerr 2006). Competing evidence exists from the USA and Europe on the impact climate change will have on plant-pollinator synchronies. Studies from Europe have shown that climate change is strongly associated with significant disruptions in plant-pollinator relationships whereas studies from the USA have shown extensive synchronies in plant-pollinator mutualisms (Bartomeus et al. 2011, 2013; Parsche et al. 2011).

### Managed Pollinators

#### **Honey Bees and Climate**

The combination of natural bee migration and exportation by humans has resulted in honey bees occupying a wide diversity of climatic zones around the world. The ability for honey bees to thrive in a variety of temperature conditions shows that they must exhibit plasticity to climate fluctuations and have genetic variation for selection of new climate-tolerant traits to act upon (Le Conte and Navajas 2008). There is one Canadian (Parker et al. 2010) and two European studies (Amdam et al. 2005; Kovac et al. 2014) that discuss the ability of honey bees to adapt to different climates. Parker et al. (2010) and Amdam et al. (2005) conducted proteomic studies that describe the cellular processes and physiological changes honey bees have evolved that have allowed them to adapt to different climates. These studies show that bees have historically adapted to different climatic conditions. In addition, Kovac et al. (2014) found that *Apis mellifera ligustica*, bees from warmer climates can tolerate exposure to higher temperatures better than *Apis mellifera carnica*, a species from cooler climates, further suggesting their ability to adapt and also speculating that some subspecies may have the ability to survive unpredictable warm weather events that could accompany climate change. Nevertheless, these studies do not explicitly study the effects of how current or projected climate change might impact honey bee populations.

It is very difficult to study the effect of climate change on honey bees in Ontario because they are non-native species in North America and are heavily managed. Humans interfere with the temperature exposure of honey bees during the coldest months of the winter by insulating their hives and sometimes using indoor overwintering facilities. Furthermore, phenological mismatches between nectar and pollen as a food source and honey bee pollination can be mediated by supplementing hives with protein and carbohydrates until appreciable forage is available. Humans can also influence the timing when crops are pollinated by transporting hives close to fields during their exact blooming periods.

In Europe, where native feral honey bee colonies exist, studies have begun to examine the role of climate on their populations. Coroian et al. (2014) suggests that different climate conditions can drive the divergence of honey bee subspecies. *Apis mellifera carnica* and *Apis mellifera macedonica* exist on either side of a mountain ridge in different climate zones of Romania. Molecular analyses determined it is the climate – not the geography – that led to the separation of subspecies. In this study the climatic zones only

varied by a few degrees Celsius. If climate-driven selection can occur from slight temperature deviations, then global warming may impact honey bee subspecies diversity. Further studies examining long-term effects of changing climates are warranted.

### **Climates and Other Managed Species**

There are no specific studies that examine the effects of climate change on managed *M. rotundata* or *B. impatiens* (Figure 8), though Sheffield (2008) examined aspects of climate suitability for the former species in Nova Scotia when used for lowbush blueberry pollination. Lowbush blueberry flowers almost a month earlier than alfalfa, so these bees (which are normally summer flyers) are released much earlier than their natural emergence period, at times when night time temperatures can drop well below freezing. Sheffield (2008) demonstrated that foraging adults may be at risk to low night time temperatures (i.e.,  $<-5^{\circ}\text{C}$ ) when used for lowbush blueberry pollination, suggesting that there are climatic suitability issues when considering managed solitary bees for crop pollination (Krunic and Hinks 1972).

The role of climate has been investigated for managed *Osmia lignaria*. Sheffield et al. (2008c) demonstrated that *O. lignaria* populations originally from Utah, but reared and wintered in Nova Scotia for one season, had slightly - but significantly - higher winter survival than populations directly imported from Utah, probably linked to increased supercooling capacity during the winter. Bees from both locations had similar natural emergence periods coinciding with apple bloom, though a slightly higher proportion of females reared in Nova Scotia emerged earlier (Sheffield et al. 2008c).

Additional peer-reviewed studies have been conducted in the USA and three more in Europe. Taken together, there is well established evidence that climate affects survivorship and emergence times of *Osmia*. *Osmia lignaria* larvae pupate in the late summer and fall and then undergo diapause as full adults before the onset of cold winter temperatures. Because *Osmia* overwinter in dark cavity nests, temperature (instead of photoperiod) serves as the main cue for when these bees choose to enter diapause. The duration of diapause is ideally timed for adult emergence to coincide with the bloom time of flowers. There are cost-benefit decisions relating to when *Osmia* enters diapause; entering early ensures the bee will avoid cold exposure, but entering too early means unnecessarily using conserved resources. There is well established evidence that the timing of eclosion (adult emergence) affects overwintering survival and emerging body condition. Bosch et al. (2010) verified that enclosing too early results in using more body fat, more weight loss, and reduced adult lifespan. When *Osmia* enter diapause, the temperature that adults experience while overwintering also affects survival. *Osmia* cannot withstand overwintering above  $10^{\circ}\text{C}$ , at these temperatures they lose body fat quickly and die of starvation (Bosch et al. 2010; Sgolastra et al. 2010, 2011). Warmer temperatures lead to higher metabolic rate (Sgolastra et al. 2010, 2011) and, most notably, earlier emergence (Bosch et al. 2010). The anticipation of longer summer temperatures and later winter onsets from climate change illustrates there could be mismatches in the timing of both the onset of *Osmia* diapause in winter and emergence in spring. Effects on managed *Megachile* and *Bombus* are not known and could be different due to their divergent life histories.

### **Phenology Shifts**

Global warming resulting in warmer, earlier springs can advance phenological shifts in flowering time and insect flight time. Theoretically speaking, evolution has led to

synchrony between flower bloom times and spring emergence of pollinators, facilitating pollination to occur during the peak floral resource provision. Climate change could result in a mismatch of phenology between plants and insects, causing flowers to bloom before pollinators have emerged, or vice versa. There is only one study that has examined the influence of climate change on the phenology of the honey bee. Gordo et al. (2010) tracked the first spring appearances of honey bees in 700 locations in Spain between 1952 and 2004. The authors found that temperature accounted for most of the variability in honey bee phenology, where warmer temperatures led to earlier honey bee appearances. Other factors such as altitude and vegetation also played a role. The honey bees in this study were naturally found in the area. The effect of phenology shifts for managed honey bees is not currently known.

### Phenology Shifts in Other Managed Bees

There have not been any studies directly measuring phenology shifts in other managed bees. Speculative evidence for phenology shifts due to climate exists for *Osmia*. Although as mentioned above, *O. lignaria* populations brought from Utah and reared and wintered for one season in Nova Scotia had similar emergence periods to bees imported direct from Utah (Sheffield et al. 2008c), although a higher proportion of females from the locally acclimated population emerged earlier. In another study Pitts-Singer et al. (2014) overwintered bees that descended from populations in northern Utah, Washington, and California in climatic conditions that mimicked those of California. The development and emergence patterns of the bees matched their geographic origin. Bees that originated from the warmer climate of California had a higher metabolism, developed slower, and survived better in the artificial California conditions than bees that originated from the cooler climates of Washington and northern Utah. This study indicates that these bees show some plasticity with regards to development in a new climatic regime, but their phenologies are largely due to heritable adaptations to their original climates. The question of whether or not *Osmia* will be able to adapt to new climates as a result of climate change still remains and has not been directly tested.

### Extreme Weather

Weather conditions can greatly impact honey bee foraging. Foragers are most effective pollinators on warm sunny days, but undergo extended periods of inactivity (Riessberger and Crailsheim 1997) and collect less pollen (Blaschon et al. 1999; Schmickl and Crailsheim 2002) when it is cool, rainy, or dark outside. Indeed, pollination for honey bees is more weather dependent than it is for other bee species. Honey bees require higher temperatures, more solar radiation, and lower wind speeds than managed *Osmia cornuta* to pollinate crops, and unlike *Osmia*, will not fly in strong wind or light rain (Vicens and Bosch 2000). Other managed bees including *Osmia* and *Bombus* species are more resilient to poor weather conditions and are not impacted as strongly as honey bees (e.g., Frier et al. 2016). Bad weather conditions extend beyond pollination to impact in-hive activities as well for honey bees; queens lay fewer eggs (Alhaddad and Darchen 1995) and nurses spend less time feeding brood when the weather is poor (Riessberger and Crailsheim 1997; Schmickl and Crailsheim 2002). Subzero temperatures during lowbush blueberry flowering could have severe negative impacts on Alfalfa leafcutter bee (*M. rotundata*) populations used for pollination (Sheffield 2008).

Honey bees are historically from warm climates in the Asian tropics and have subsequently adapted to withstand colder winters experienced in North America and Europe. Despite their abilities to store winter food reserves and thermoregulate in tight



clusters, long or extremely cold winters can result in colony death. Ontario beekeepers have experienced some uncharacteristically high overwintering losses of 37% in 2007 (OMAFRA 2007), 43% in 2011 (Kozak 2012b), 58% in 2014 (Kozak 2015a), and 38% in 2015 (CAPA 2015). Long and harsh winters only account for some of the colony loss, however. The overall patterns of colony loss are due to interactions between a range of factors, including weather, pests, pathogens, diseases, and management practices.

### **Indirect Effects of Climate**

Climate change may additionally cause indirect stress for honey bees when it interacts with other factors. For example, pests and pathogens may become a greater burden in the face of warming temperatures. The small hive beetle, *Aethina tumida*, is naturally found in South Africa where it does not cause significant harm to African honey bees (*Apis mellifera capensis*). Transportation by humans has unintentionally brought the beetle to North America, where it thrives in hot and humid regions in the USA and has recently entered Southern Ontario. The beetle has more of an impact on honey bee colonies in North America because they have not yet had the time to develop defences. Currently, the region this beetle can survive in is limited by warm climates, but global warming could expand its range. Varroa mite populations are also influenced by climate. Longer springs result in longer brood periods, which significantly increases varroa mite levels (Fuchs 1990). Additionally, *Nosema ceranae* is more likely to survive and infect colonies at higher rates in warmer climates (Gisder et al. 2010).

Climate change may also alter the distribution and diversity of flower species. Wetter summers or uncharacteristic dry conditions could affect which floral types are found in a given area and the amount of pollen and nectar that they produce. Because honey bees depend on a variety of floral sources and sufficient pollen and nectar to remain healthy, these downstream effects of climate change could impact the type and quality of nutrition that honey bees receive (Le Conte and Navajas 2008). There are currently no studies that investigate this relationship between climate and forage quality for honey bees, but research in this area would be beneficial.

## **Wild Pollinators**

### **Distribution Shifts**

The current distributions of most pollinator species in Ontario are poorly known. Therefore, understanding how species are shifting their distributions to cope with climatic changes is even less well understood. There is very limited evidence that pollinator species from Ontario may shift their distributions as a means for coping with increasing temperatures. One study from Ontario has looked at the influences increasing temperatures have had on the distribution of a carpenter bee species, *Xylocopa virginica* (Linnaeus, 1771). This study found that predicted summer and winter temperatures may limit the species ability to persist northward (Skandalis et al. 2011). A second study from Ontario examining the impacts of climate change on pollinators found that bumble bee species with greater climatic specialization are at greater risk of decline (Williams et al. 2009). This study also reported that species living close to their maximum climatic tolerances are more at risk of decline and, ultimately, extinction (Williams et al. 2009).

There are significantly more studies that have investigated the impact of climate change on distribution shifts of butterflies compared to these shifts in bees. There is well established evidence from Ontario and Canada on the impacts of climate change on

butterfly populations. Several studies have reported that butterfly species are predicted to track climate change by moving northward (Coristine et al. 2016; Kerr 2001; Kerr et al. 1998; Kharouba et al. 2009). However, studies to date conclude that pollinators have been unable to extend their ranges as fast as required to keep pace with climate change (Bedford et al. 2012; White and Kerr 2006).

In Europe, studies have shown that pollinator assemblages have shifted in recent years to buffer against changes in climatic conditions. A study from a mountainous region in Northern Sweden found that over an extended period of time pollinator assemblages did not differ significantly. Species richness of butterflies and moths increased slightly, but no significant difference in the number of wild bee species were found (Franzen and Ockinger 2012). This result is inconsistent with the view that pollinators are unable to cope with increasing temperatures (Sinclair et al. 2013). Further, this result does not agree with other studies that have found evidence that climate change has negatively affected species and communities over time (Ovaskainen et al. 2013). Furthermore, there is evidence that species have been moving up mountain ranges and receding at their southern ranges as a means to cope with rising temperatures (Wilson et al. 2005). These findings agree with a recently published study that showed climate change has negatively impacted bumble bees on two continents (Kerr et al. 2015). Specifically, using over 400,000 observations of 67 species from North America and Europe, the study tested whether species geographical range, realized physiological niche limits with regards to temperature and altitude shifted over time relative to a baseline time period. Kerr et al. (2015) found that climate change exerts strong effects on southern range margins in both Europe and North America, but that bumble bee species ranges have not expanded northwards, and that this has reduced overall ranges increasing prospects of climate-driven pollinator extinction and deficits of ecosystem services.

### **Phenology Shifts**

We found no evidence from Ontario directly examining the impacts climate change is predicted to have on pollinator phenology. However, a USA study has shown that over the past 130 years the phenology of 10 bee species from the northeastern USA have advanced approximately 5 days (Bartomeus et al. 2011). This study has direct relevance as the species investigated also occur in Southern Ontario. Unlike many studies that have reported significant phenology shifts in pollinators, this study has indicated that when comprehensive data measuring rates of advance for plants, the rates were not distinguishable from those of bees, suggesting no mis-match in plant-pollinator synchronies at least among generalist species examined (Bartomeus et al. 2011). Studies that have examined phenology shifts in other native pollinators have also shown they are advancing the timing of their seasonal flight period (Hegland et al. 2009; Kerr et al. 1998). Other results have shown that butterfly species on average bring their flight date forward by 3.6 days/°C (Polgar et al. 2013).

### **Plant-Pollinator Synchrony**

There is some competing evidence from the USA and Europe that have indicated that climate change is impacting the synchronicity of plant-pollinator interactions (Bartomeus et al. 2011, 2013; Forrest and Thomson 2011; Memmott et al. 2010; Petanidou et al. 2014; Polce et al. 2014; Thomson 2010). Studies from Europe suggest that climate change is strongly associated with significant disruptions in plant-pollinator relationships (Memmott et al. 2007; Petanidou et al. 2014). Two studies conducted in the Rocky Mountain research lab in Colorado have suggested that phenology of plants and trap-nesting bees and wasps



is regulated in similar ways by temperature, but that plants are more likely than insects to advance phenology in response to springtime warming (Forrest and Thomson 2011; Thomson 2010). In contrast, two studies conducted over significantly greater extended periods of time have found extensive synchrony between bee activity and apple peak bloom (Bartomeus et al. 2013).

When plant-pollinator relationships are disturbed, the risk of greater ecological community mis-matches also increases. Many studies have modelled the impact of climate change on plant-pollinator synchronies and predicted that they will be significantly affected over time (Hoover et al. 2012; Polce et al. 2013, 2014). That is, predictive models generally suggest that most future suitable habitats for crop pollination corresponded to low pollinator availability (Hoover et al. 2012; Polce et al. 2014). To accurately test whether population and community synchronies are affected by climate change, extensive long-term datasets are required. That is, changes in synchronies are more readily detected over longer periods of time rather than examining changes over shorter periods. When examining changes in advancement several studies have tested this over extended periods of time using ecological community data from habitats that experience annual weather fluctuations (Gordo and Sanz 2005; Petanidou et al. 2014) and have indicated that among plants with different life histories, annual plants were more severely affected by plant-pollinator mis-matches than perennials (Petanidou et al. 2014).

Results demonstrating no changes in plant-pollinator synchronies with regards to wild pollinators are consistent with the hypothesis that increased levels of biodiversity in habitats buffer against the impacts of climate change (Bartomeus et al. 2013; Brittain et al. 2013a; Rader et al. 2013). This is due to bee species showing a variety of responses to increased temperatures. Specifically, Bartomeus et al. (2013) found there were large shifts in community composition, as demonstrated by 56% of bee species showing significant changes in relative abundance over time. These results show that some species are more vulnerable to climate change than others, and traits associated with a declining relative abundance include specialized dietary needs, short flight periods and large body size.

Information from the United Kingdom indicates there is currently large spatial overlap between plants and pollinators in orchards, but predicts that by 2050 there will be significant plant-pollinator mis-matches that will not only affect wild species but will also start to affect the large spatial distribution of orchard pollinators (Polce et al. 2014). That is, most future suitable habitats for crop pollination corresponded to low pollinator availability. These results are not consistent with evidence from the USA, and a plausible explanation is that species from Europe may have exceeded their geographical range limits compared to species found in North America.

### Extreme Weather Events

One Canadian reported it is easier to overwinter *Osmia lignaria* bees that have spent some time in the local climate region. Survival rates were higher for progeny of bees raised locally for one generation, compared to progeny of imported bees from other climate regions (Sheffield et al. 2008c). This demonstrated that *Osmia* can be managed in Canadian climates.

One study in the USA found that honey bees were more affected by extreme weather events than wild pollinators (Brittain et al. 2013a). Specifically, honey bees decreased their visitation rate to blooms on almond trees in high winds, whereas flower visits by wild bees were unaffected. Another study found that specialist bee species are more likely to go

extinct compared to generalist species (Minckley et al. 2013). In Europe, there is some evidence that increasingly frequent weather extremes, particularly heat waves, are associated with climate change and have caused localized *Bombus* population declines in France (Rasmont and Iserbyt 2012). Furthermore, extreme temperatures can disrupt thermoregulation of overwintering bumble bee colonies and consequently result in low colony fecundity the following season (Weidenmüller et al. 2002). Several physiological adaptations to withstand extreme temperature events have been identified in hymenopteran taxa (Sinclair et al. 2013), however, there is very little evidence suggesting wild pollinators have any specific mechanisms to increase their thermal tolerance when faced with extreme temperatures (Owen et al. 2013).

### Suggestions

- To date, limited research has been conducted examining the impacts of climate change on pollinators in Canada, including Ontario.
- Very few studies have examined distributional shifts in wild pollinators other than butterflies. This represents a very significant knowledge gap that requires urgent attention. Given there is limited evidence on the impacts of extreme weather events on honey bees, we recommend future studies investigate potential impacts of extreme weather events might continue decreasing honey bee (and wild pollinator) visitation rates for crops.
- Competing evidence from the USA and Europe on the impacts climate change will have on the synchrony between plant and pollinator phenology highlights the need to continue to monitor these important relationships. If climate change continues to affect plant-pollinator relationships, this will have important implications for global crop pollination.
- Few, if any, pollinator monitoring studies have been completed north of Algonquin Provincial Park. If pollinator species are shifting their distributions northwards in response to rising temperature, monitoring northern locations is imperative as changes in species richness will be more evident in northern locations compared to sites that are already well within current species ranges.
- Finally, there is significant need to establish a long term pollinator monitoring program for Ontario. Evidence for the distribution and species richness of pollinators is particularly lacking in the northern parts of the province.

### AGROCHEMICALS

The risks to pollinators of exposure to agrochemicals, including pesticides (insecticides, fungicides, herbicides and miticides) and antibiotics, are well documented (Batra 1981; Cutler et al. 2014a; Desneux et al. 2007; Potts et al. 2010). Pesticides are commonly used in seed treatments and foliar sprays to prevent pests from feeding on agricultural crops. While pollinators are not the targets of these treatments, they can be significantly affected by applications of these agrochemicals (Johnson et al. 2010; Mullin et al. 2010; Hunt and Krupke 2012; Raine and Gill 2015). The severity of any impacts depends on a number of factors, including agrochemical toxicity, dosage, duration of exposure (acute versus chronic effects), mode of action (e.g. neurotoxin versus insect growth regulator) and type of exposure (e.g. oral versus contact exposure). Using insecticides as an example, the potential exposure for insect pollinators would be quite different comparing exposure to spray applications during a crop bloom period versus neonicotinoid exposure from a seed treatment. Pollinators foraging on a crop spray treated during bloom will be exposed to

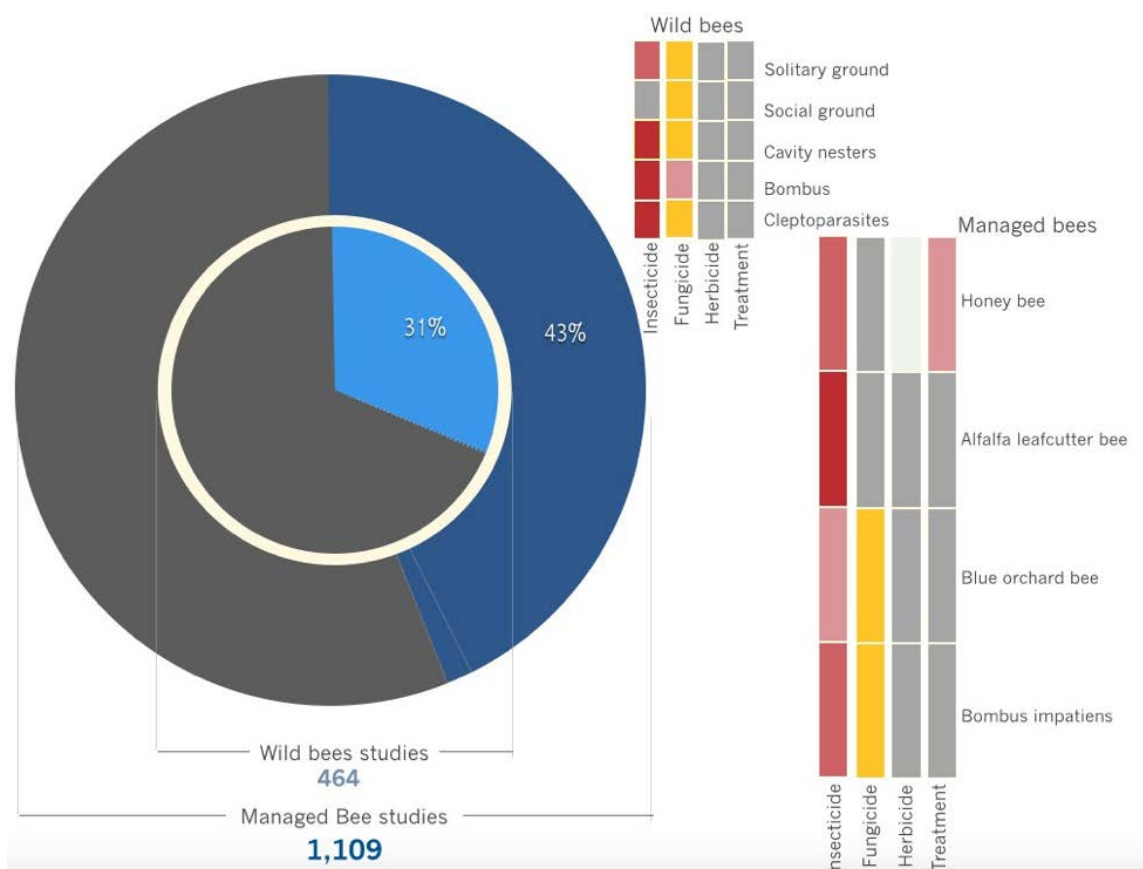
insecticide residues via contact exposure as they manipulate flowers to extract nectar and/or pollen. Acute effects are likely to be more significant in this scenario as insecticide residue levels will be comparatively high during and directly after spray application. In contrast, pollinators foraging on flowers of neonicotinoid seed-treated crops will be exposed to a low dosage of active ingredient in nectar and/or pollen collected on every visit – chronic, oral exposure. In addition to potential direct exposure to a wide range of agrochemicals outside their nest (Henry et al. 2012a), foraging individuals will bring some of these back to their nest or colony providing a potential route for exposure to larvae. In social bees, agrochemicals can also accumulate in different members of the colony, as well as in hive products such as wax, honey or royal jelly. Despite the wide diversity of pollinators, honey bees tend to dominate studies of agrochemical impacts due to their use and exposure in agricultural systems, and their pivotal role as a test species for regulatory toxicity testing.

There is well established evidence that pesticide exposure can be hazardous to pollinator health (Hunt and Krupke 2012; Johnson et al. 2010; Mullin et al. 2010), effects that may be exacerbated by combined exposure to multiple chemicals (e.g. Colin and Belzunces 1992; Gill et al. 2012; Johnson et al. 2013; Thompson and Wilkins 2003; Thompson et al. 2014). Historically, exposure studies have relied extensively upon laboratory assays using a range of agrochemical concentrations to determine mortality rates and dosage response curves for acute oral or contact exposure. More recently, there has been considerable research into potential sublethal effects of agrochemicals, particularly insecticides, on pollinators. These studies have reported sublethal impacts including reduced longevity of adult bees, impaired foraging, altered learning and memory performance, decreased navigational abilities, and reduced colony development and reproduction (Barbosa et al. 2015; Bryden et al. 2013; Davis et al. 1988; Desneux et al. 2007; Gill et al. 2012; Gill and Raine 2014; Godfray et al. 2014, 2015; Henry et al. 2012b; Matsumoto 2013; Stanley et al. 2015a, 2015b; Stanley and Raine 2016; Taylor et al. 1987; Whitehorn et al. 2012; Williamson et al. 2014). Overall, it is important to consider the potential toxicity of the reported agrochemical, as variation in dosage levels, exposure scenarios and applications can have diverse effects. In addition to these considerations of hazard, we must also consider possible routes of exposure. Without such routes of exposure the risk of even a potentially highly hazardous agrochemical is low ( $\text{Risk} = \text{Hazard} \times \text{Dose (Exposure)}$ ; Ropeik 2002). Aspects of these considerations and their known toxicological effects on pollinators are discussed below.

### Summary of Evidence

While there is significantly more evidence for the impacts of agrochemicals on managed- compared to wild pollinators, the majority of studies from Ontario examine the effects of pesticides on honey bees. A major focus of this research has been to determine the effects of pest and pathogen treatments for honey bee health, particularly formic acid; a widely promoted miticidal treatment that appears to have numerous negative effects on honey bee health. Due to the development of resistance to commercial synthetic miticides, researchers across Canada are testing a range of natural alternatives including essential oils. Some of these alternative treatments show dose dependent toxicity for honey bees, although these effects also depend strongly on the method of application. Despite the widespread use of fungicides and herbicides in agriculture there is limited evidence from research in Ontario, Canada, or around the world on the effects of these agrochemicals on honey bees, other managed pollinators or wild bees (Figure 9). There is conflicting evidence for the impacts of neonicotinoid insecticides on honey bee health, but there is

established but incomplete evidence that this class of insecticides have negative impacts on other managed bee species. This evidence from Ontario is strengthened by established but incomplete evidence from laboratory, semi-field and field studies conducted predominantly in Europe and the USA. However, insecticide impacts deserve further study for a wider range of managed and wild bees, as the current evidence suggests that species respond rather differently to comparable levels of exposure depending on a range of factors including their ecology, life-history and degree of sociality. Living in large, perennial colonies appears to make honey bees in particular relatively resilient to insecticide impacts compared to bumble bees and solitary bee species.



**Figure 9.** Pie chart illustrating the percentage of unique relevant studies that investigated the impacts of agrochemicals on both wild (light blue sector, inner circle) and managed bees (dark blue sector, outer ring). The literature consensus tables, shown on the right side of this figure, demonstrate the impacts of agrochemicals on wild and managed bees. Green indicates the factor has a positive effect on pollinators, yellow indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory, and red indicates the factor has a negative effect on pollinators. Grey cells in the consensus table represent current knowledge gaps (for more details see page 20).

## Managed Pollinators

### **Insecticides**

Studies in Ontario suggest that organophosphates (Harris and Svec 1969; Helson et al. 1994) and carbamates (Davis et al. 1988; Harris and Svec 1969; Helson et al. 1994) can have negative consequences for honey bee health. At sublethal dosages, both carbamates and organophosphates lead to reductions in worker longevity, colony weight gain, and brood production and also increase variability in acetylcholinesterase levels (Bailey et al. 2005; Davis et al. 1988). The pyrethroid cyhalothrin is intermediately toxic to the honey bee and highly toxic to *M. rotundata* when analyzing their direct mortality. Sublethal effects were also observed, as insecticide exposed honey bees visited flowers less frequently and exposed *M. rotundata* experience population reductions at nesting sites (Mayer et al. 1998). Pyrethroid toxicity was significantly affected by mixing with adjuvants for both these bee species.

There is conflicting evidence for the effect of neonicotinoids on honey bee health. The three studies conducted to date in Ontario all report no measurable negative effects from exposure to these agrochemicals. Laboratory feeding trials using pollen collected from neonicotinoid field-treated corn had no effect on worker mortality. Likewise honey bees exposed to corn tassels in fields grown from imidacloprid and/or clothianidin treated seed showed similar levels of mortality to untreated controls (Bailey et al. 2005). Similarly, field studies have also reported no effect of colonies being exposed to neonicotinoids by proximity to seed-treated crops on honey bee mortality (Cutler and Scott-Dupree 2007; Cutler et al. 2014a). In both studies hives were placed in neonicotinoid treated canola fields during bloom and recorded various parameters of colony growth and health for 130 days. Cutler and Scott-Dupree (2007) reported no differences in bee mortality, worker longevity, brood development, colony weight gain, overwintering losses, and honey production between control and treatment groups. Results from Cutler and Scott-Dupree (2014a) mirror the findings of their earlier field study, and also reported no changes in pest incidence, number of adults, and quantity of sealed brood. While residue analysis indicates that bees in these studies were only exposed to low levels of neonicotinoids ranging from 0.5-2.0 parts per billion (ppb) while they were foraging (Cutler et al. 2014b), some samples from control locations were found to contain detectable levels of neonicotinoids. Results from another two studies from the rest of Canada report different results suggesting there are impacts of neonicotinoid exposure for honey bees. Boily et al. (2013) detected elevated levels of acetylcholinesterase in bees following neonicotinoid exposure, and neonicotinoids were confirmed as the most likely main contributor of 79 of 110 reported incidences of honey bee colony kill incidents reported in Canada in 2007 (Cutler et al. 2014a). Two large-scale field studies conducted in Europe also reported no measureable impacts of exposure to either corn or canola crops seed-treated with neonicotinoids. Although conducted over a 4-year period, the limited levels of field-scale replication and the absence of statistical analyses make it challenging to robustly interpret results from the French studies (Pilling et al. 2013). In contrast, the recent Swedish study was the most highly replicated to date including 16 fields: 8 planted with clothianidin-treated and 8 fields without. Even with such a large-scale study the authors' own power analysis indicates that they would have been unable to detect a treatment effect smaller than 19% in terms of honey bee colony growth (Rundlöf et al. 2015). This suggests it may be unrealistic to conduct field scale experiments with the power to robustly demonstrate the absence of neonicotinoid impacts on honey bee colonies given constraints of landscape, budget and manpower.

Understanding the responses of other managed bees to insecticide exposure is similarly complex. An Ontario study examining the impacts of two neonicotinoids (clothianidin and imidacloprid) and two other insecticides (the pyrethroid deltamethrin and bacterially-derived spinosad) on three managed bee species used in the province (*M. rotundata*, *O. lignaria*, *B. impatiens*) suggested that the two neonicotinoids were more toxic compared to the other insecticides (Scott-Dupree et al. 2009). Results from this direct application study also show that the toxicity of each insecticide was highly variable across bee species. For example, deltamethrin was highly toxic to *M. rotundata*, but much less toxic to *O. lignaria* and *B. impatiens*. Differences in species susceptibility to insecticide exposure may depend in part on physiological differences, foraging behaviour, nesting strategy, and other factors. Another Ontarian study reported the neonicotinoid imidacloprid reduces life span and fertility when fed to managed *B. impatiens* (Gradish et al. 2010). A Canadian lab and field study exposed *M. rotundata* and *O. lignaria* to lethal and sublethal doses of imidacloprid and clothianidin and examined their responses. There were no observed mortalities in either bee, but sublethal effects in the form of delayed larval maturation were detected following exposure to imidacloprid (Abbott et al. 2008). Results from a recent cage study in Europe reported severe detrimental impacts of chronic exposure to field-realistic neonicotinoid dosages in the managed pollinator, *Osmia bicornis* (Sandrock et al. 2014). While neonicotinoid exposure did not affect adult bee mortality, it resulted in an almost 50% reduction in overall offspring production and a significantly male-biased offspring sex ratio. These laboratory impacts seem are consistent with field results from Sweden reporting complete failure of *O. bicornis* females to provision nest cells in any of their 8 neonicotinoid treated canola fields (compared to successful brood cell building in 6 of 8 control fields: Rundlöf et al. 2015).

Other insecticides have also been studied in Ontario with conflicting results. Honey bees exposed to Fonofos-treated corn through cage and field experiments showed similar levels of mortality to control colonies in a 1991 study (Kevan 1991), although this organophosphate pesticide was subsequently banned in Canada in 2000 due to its overall toxic properties. A study examining whether neem insecticides would deter honey bees from pollinating canola found that they are deterred under laboratory, but not field, conditions (Naumann et al. 1994). Studies like these stress the importance of ensuring dosage and exposure profiles are as field-realistic as possible (ideally performed in the field) and of replicating such studies to determine consistent effects of insecticides. A study from the USA examining the effects of a phenylpyrazole insecticide, Fipronil, reported this agrochemical is intermediately toxic to honey bees and highly toxic to *M. rotundata* (Mayer and Lunden 1999). Like the pyrethroid mentioned earlier, adjuvants were also found to increase the toxic effects of fipronil depending on the concentration and bee species considered.

To date, three studies have examined the impacts of insecticides on managed bumble bee (*B. impatiens*) colonies in Ontario. The first found abamectin, metaflumizone and chlorantraniliprole significantly increased worker mortality at both medium and high concentrations (Gradish et al. 2010). Four out of five insecticides tested (spinosad, spinetoram, phosmet and deltamethrin) were found to be toxic when directly applied to bees, with deltamethrin being the most toxic and flubendiamide showing no measurable toxic impact (Gradish et al. 2012). In addition to toxicity measured as direct worker mortality, sublethal effects were also studied. Higher concentrations of deltamethrin led to changes in worker life span, nectar consumption, and number of males produced. These studies provide evidence that managed bumble bees are susceptible to several common

insecticides used in Ontario. Results from a field study comparing the performance of *B. impatiens* colonies placed at the edges of neonicotinoid seed-treated and organic corn (maize) fields reported very limited collection of maize pollen by any colonies (Cutler et al. 2014b), suggesting this is unlikely to be a significant source of insecticide exposure for bumble bees. However, colonies placed by neonicotinoid-treated fields produced fewer workers than those on organic farms.

There is considerable evidence from outside Ontario reporting measurable impacts of insecticide exposure on managed bumble bee colonies (both *Bombus terrestris* and *B. impatiens*). Laboratory studies have reported negative impacts of neonicotinoid exposure on feeding rate (Cresswell et al. 2012; Elston et al. 2013), learning and memory (Stanley et al. 2015b; Piiroinen and Goulson 2016, but see Piiroinen et al. 2016), wax cell construction (Elston et al. 2013), brood production (Laycock and Cresswell 2013; Laycock et al. 2012, 2014, Tasei et al. 2000), colony growth (Bryden et al. 2013; Fauser-Misslin et al. 2014) and colony reproductive output (Fauser-Misslin et al. 2014). Although apparently unable to taste neonicotinoids in solution, both bumble bees (*B. terrestris*) and honey bees appear to choose treated sugar water feeders over untreated controls under laboratory conditions (Kessler et al. 2015). Results from semi-field studies in which field-realistic exposure to neonicotinoids was used have reported negative effects on pollen foraging performance (Gill et al. 2012; Gill and Raine 2014; Feltham et al. 2014; Stanley et al. 2015a), flower handling (Stanley and Raine 2016), reduced or delayed colony growth (Arce et al. 2016; Gill et al. 2012; Whitehorn et al. 2012; Larson et al. 2013) and reduced male (Arce et al. 2016) and queen production (Arce et al. 2016; Whitehorn et al. 2012; Larson et al. 2013). Assessments of exposure to neonicotinoid residues in agricultural landscapes suggest *B. terrestris* colonies grow more slowly (Rundlöf et al. 2015) and produce fewer males (Rundlöf et al. 2015; Ellis et al. 2017) and new queens (Rundlöf et al. 2015; Goulson 2015, but see FERA 2013). There is also evidence suggesting combined exposure to insecticides (the neonicotinoid imidacloprid and pyrethroid lambda-cyhalothrin) enhances toxicity compared to exposure to either active ingredient alone (Gill et al. 2012), and interactive effects between neonicotinoid (Thiamethoxam) exposure and parasite (*Crithidia bombi*) infection on mother queen (foundress) survival (Fauser-Misslin et al. 2014: see also page 70).

## Fungicides

We found no studies that have examined the effect of fungicides on honey bees, *M. rotundata* or *O. lignaria* in Ontario or Canada. However, one Ontarian study has investigated the potential impact of the greenhouse fungicides myclobutanil, potassium bicarbonate and the combination of cyprodinil + fludioxonil on managed *B. impatiens* colonies (Gradish et al. 2010). Bumble bees are most often used for pollination services in closed greenhouses where they are unable to choose to forage on non-sprayed foliage. It is therefore very important to know whether fungicides (and other agrochemicals) used in greenhouses are toxic to bumble bees. Assays of direct contact toxicity and sublethal toxicity indicated that none of these fungicides had negative impacts for *B. impatiens* across the concentration range measured.

Results from a Nova Scotia study examining whether yields of lowbush blueberry (*Vaccinium angustifolium*) were affected by fungicide treatment (the experimental design included two intensities of pollination, 25% or 100% of flowers, and two levels of fungicide treatment), showed that increased levels of fruit set were only possible with full pollination and full fungicide treatment (Melathopoulos et al. 2014). Overall, the results of

this study suggest that pollinator activity in lowbush blueberry fields is dependent upon agrochemical disease management practices.

Bees will often be exposed to fungicides and insecticides on treated crops, and honey bees could also experience combined exposure to fungicides and miticides inside their colony. There is some evidence from the USA of combined exposure to fungicides and miticide exacerbating toxic effects for honey bees (Johnson et al. 2013), and of synergism between neonicotinoid insecticides and fungicides for both honey bees and *Osmia cornifrons* when using formulated product in mixtures as they are commonly applied in apple orchards (Biddinger et al. 2013).

### Herbicides

There are no studies in Ontario that investigate the impacts of herbicides on honey bees. A lab study in Quebec used field realistic levels of the herbicides atrazine and glyphosate (RoundUp®) to investigate their impacts on acetylcholinesterase activity (Boily et al. 2013). Chronic exposure to moderate dosages of atrazine significantly reduced acetylcholine protein levels, and glyphosate at moderate and higher doses reduced both protein levels and tissue concentration of acetylcholinesterase. This one study provides some evidence that herbicides have a negative impact on honey bees, but more research is needed to strengthen our understanding in this area.

### Pest and Pathogen Treatments

The majority of agrochemical studies in Canada examine the safety of treatments used to control pests and pathogens in an effort to find safe, effective alternatives to the commercial miticides. *Varroa* mites are becoming resistant to the active ingredients of these treatments. In Ontario, Gashout and Guzman-Novoa (2009) examined the toxicity of natural varroa treatments and found that some essential oils are actually toxic to honey bees. Of the 22 natural products they tested, thymol and clove oil were the most toxic to adult workers and thymol was the most toxic to larvae, and many of the essential oils tested were as toxic as tau-fluvalinate (Apistan®), a commercial synthetic pyrethroid miticide. Canadian studies continue to examine the effects of alternative natural mite treatments on honey bees, and nearly all report some negative consequences for bee health. Neem oil has been shown to reduce brood populations, increases queen loss, and deter workers, but does not affect worker mortality (Melathopoulos et al. 2000a). Canola oil (Melathopoulos et al. 2000b), pulegone, phenyl ethyl alcohol, cinnamic aldehyde, citronella and alpha-terpineol all resulted in over 70% worker mortality in studies looking at various concentrations (Lindberg et al. 2000). In contrast, oxalic acid is a natural alternative that appears to benefit honey bee colonies. Application of this organic acid results in higher honey production and summer brood populations (Giovenazzo and Dubreuil 2011).

In Ontario, beekeepers are encouraged to rotate their usage of commercial synthetic miticides with formic acid (OMAFRA 2014b), however there is well established evidence that formic acid – although successful in treating mites – has detrimental health implications for honey bees. Canadian studies have found formic acid increases worker and queen mortality, in addition to overall colony loss, at different rates depending on concentration, application method and temperature (Giovenazzo and Dubreuil 2011; Lindberg et al. 2000; Underwood and Currie 2003, 2004, 2005, 2007). Formic acid has also been found to reduce brood populations (Westcott and Winston 1999). Only one study reports beneficial results from using formic acid. Currie and Gathen (2006) found



spring applications resulted in higher honey production.

Canadian research has shown that formic acid application technique, and the level of mite infestation when treatment is applied, affect honey bee colony health. When a colony is infested, 'slow release' formic acid improved colony development, but reduced it in hives with no varroa. There were no changes in colony development when formic acid was applied with the 'pour on' method (Ostermann and Currie 2004). Furthermore, formic acid leads to reduced honey production when applied as Mite Away® strips, but it was higher when applied to the bottom board of hives (Giovenazzo and Dubreuil 2011). These studies shed light on the most effective and least risky ways to treat mites using formic acid.

The commercial miticides licensed for use in Ontario are Amitraz (Apivar®) and Tau-fluvalinate (Apistan®). The only Canadian study to examine the effects of Amitraz on bee health to date found it led to increased worker mortality at higher doses (Hillier et al. 2013). There is conflicting evidence on the impacts of Apistan® for bee health. Some studies report that it does not affect worker longevity, colony honey production, population size or foraging activity (Westcott and Winston 1999), and that application results in higher honey production and lower rates of overwintering colony loss (Currie and Gatién 2006). In contrast, other studies report negative impacts on honey bee learning, memory, responsiveness to sucrose and worker survival (Frost et al. 2013). Apistan® has also been found to cause honey bee mortality (Hillier et al. 2013). These differences in reported results may be due to the concentration used, the timing or technique of application. For instance, bees experience more negative effects following oral compared to topical exposure to Apistan® (Frost et al. 2013). More research is needed to determine the most effective treatments and application regimes for varroa and tracheal mites that are least detrimental for honey bees.

### **Other Chemicals**

One Ontario study examined the effect of *Bacillus thuringiensis* on honey bee health (Bailey et al. 2005). Pollen from transgenic Bt corn was fed to honey bees and additionally the bacteria were applied directly to bees, and mortality was measured. Mortality rates did not differ among treatment groups, suggesting *Bacillus thuringiensis* does not increase honey bee mortality at these levels. Additional experiments examining other sublethal health parameters should be conducted.

## **Wild Pollinators**

### **Insecticides**

We found limited and speculative evidence from Ontario on the effects of insecticides on wild pollinator health. Helson et al. (1994) tested the effects of six insecticides, permethrin, mexacarbate, aminocarb, fenitrothion, carbaryl and trichlorfon through a laboratory dose-response design on four species of bees, *A. mellifera*, *Andrena erythronii*, *M. rotundata*, and *Bombus terricola*. This study found that insecticides typically ranked in order of decreasing toxicity: permethrin, mexacarbate, aminocarb, fenitrothion, carbaryl and trichlorfon on the wild bees. In addition, the bees ranked from the most to least susceptible in the order of *A. mellifera*, *A. erythronii*, *M. rotundata*, and *B. terricola* (Helson et al. 1994). Szabo et al. (2012) analysed a large dataset of bumble bee occurrence records and agricultural census data and showed that pesticide use (insecticides) is unlikely the major cause of decline of bumble bees in Ontario. Collectively the results of these studies are conflicting with a large body of well established global literature that has

demonstrated insecticides cause acute mortality to adult (worker) bumble bees (Gill et al. 2012; Scholer and Krischik 2014; Goulson 2015).

Studies from Canada show conflicting evidence on the effects of insecticides on wild pollinators. For example, Morandin and Winston (2003) completed experiments testing for lethal and sublethal effects of the transgenic proteins Cry1Ac and chitinase, and the chemical seed and soil treatment imidacloprid on bumble bees (*Bombus occidentalis* and *B. impatiens*) in British Columbia. Results showed that after bee species were exposed to realistic levels of Cry1Ac, chitinase and imidacloprid found in pollen, no effects were found on colony characteristics (pollen consumption, bumble bee worker weights, colony size). However, this study reported that bees in the high-imidacloprid treatment had longer handling times on complex artificial flowers than bees in the other treatments, but not at field-realistic residue levels. Interestingly, Gradish et al. (2012) report rather different results for *B. impatiens* tested using the same treatments as Morandin and Winston (2003). These authors found that *B. impatiens* was susceptible by topical exposure to all tested insecticides except flubendiamide (Gradish et al. 2012). These contrasting results demonstrate the importance of scientific rigour when examining the effects of agrochemicals on pollinator species. Though the same treatments were used in both studies, interpretation becomes difficult due to the conflicting nature of the results.

We also found published evidence from the USA and Europe that examined the impact of insecticides on wild pollinators. Evidence from California suggests declines in both butterfly species richness, and also abundance of individual butterfly species, are associated with increased neonicotinoid insecticide use while controlling for land use and other factors (Forister et al. 2016). This study also reported these correlative effects of neonicotinoid insecticides to be more severe for smaller-bodied butterfly species (Forister et al. 2016). An analysis of data for 62 wild bee species over the 18-year period in which neonicotinoid seed treatments were taken up for widespread use in oilseed rape in the UK reported significant negative impacts on species persistence associated with neonicotinoid use (Woodcock et al. 2016), with those bee species that forage on this crop being affected substantially worse.

### **Fungicides**

We found no evidence assessing the impact of fungicides on wild pollinators from Ontario. However, there was one study from Alberta testing the effects of a widely used fungicide, Benomyl, in native grasslands (Cahill et al. 2008). The authors examined plant, fungal and floral visitation after 3 years of the fungal suppression and found that there was a shift in community composition from large-bodied bees to small-bodied bees (Cahill et al. 2008). This study highlights that mycorrhizal fungi are clearly an important driver for plant-pollinator community structure and can potentially disrupt pollination services. These results provide conflicting evidence of fungicide impacts compared to those conducted on managed pollinators in the laboratory (Gradish et al. 2010; Melathopoulos et al. 2014), suggesting a clear need for more research investigating effects of agrochemicals on population dynamics and community structure.

## Herbicides

Overall, we found no evidence of herbicide impacts on wild bees including Ontario. However, there is evidence from Canada that herbicides can have negative impacts on butterflies (Russell and Schultz 2009). In recent years, restoration strategies have included the use of herbicides to control invasive plants in butterfly habitats. Russell and Schultz (2009) investigated the potential impacts of commonly used herbicides, graminicides (fluazifop- p-butyl and sethoxydim) and a surfactant (Preference) on two butterfly species. Results indicated that wing size and pupal weights of *Pieris rapae* were reduced by herbicide treatments, whereas *Icaricia icarioides blackmorei* experienced a significant reduction in development time. This study demonstrates the potential risk that non-target organisms may be exposed to herbicides including spray drift. Given that studies have shown that consequences of landscape alteration and habitat modification on pollinators have direct implications for plant mating systems, plant population persistence and community dynamics (Vanbergen 2014; Winfree 2010) it is critical that future studies investigate the effect herbicides will have on the availability of potential foraging and nesting resources for wild bee species and other pollinators.

## Suggestions

There remain significant knowledge gaps in our understanding of how widely used agrochemicals could be affecting managed and wild pollinators, either as individual chemicals or in combination. For insecticides (including but not limited to neonicotinoids) it is important to conduct research to determine the sublethal impacts that could occur following chronic exposure and/or exposure to multiple agrochemicals. Research is lacking on large scale, chronic exposure at field-realistic levels of exposure. Given that evidence to date suggests pollinator species vary considerably in their responses to similar levels of insecticide exposure, it would be very helpful to investigate agrochemical impacts in a wide range of both managed and wild pollinators across all stages of their lifecycles (in particular, very little is currently known about potential impacts of exposure to larvae). These avenues of research could form the basis for selecting possible model species to add alongside honey bees to characterize the risks of agrochemical usage to a wide range of pollinators as part of registration and licensing procedures.

The impacts of the 2015 restriction on the usage of neonicotinoid seed-treatments for corn (maize) and soy in Ontario (<https://www.ontario.ca/page/neonicotinoid-regulations>) should be assessed through widespread, long-term monitoring of pollinators (both managed and wild pollinators), soil and water quality to allow us to determine the effectiveness of this policy intervention at reducing exposure and improving pollinator health in Ontario. While the impacts of exposure to neonicotinoid insecticides for pollinators has received considerable recent attention around the world, we need to ensure alternative agrochemical options for pest control are subject to similar levels of scrutiny. It would be unfortunate if the recent focus on the risks from neonicotinoids led unintentionally to broader use of alternative pesticides that prove to be more harmful to insect pollinators and the essential ecosystem services that they provide.

Despite the widespread use of fungicides and herbicides in agriculture, there is limited evidence from research on the effects of these agrochemicals on honey bees, other managed pollinators, and wild bees. These are large and important gaps in our knowledge that need to be addressed. Pollinators are likely to be exposed to fungicides and herbicides alongside insecticides (plus adjuvants and surfactants) in agricultural landscapes. Studying the impacts of such potentially complicated and variable combined exposure scenarios

will be challenging, but important to attempt in order to understand the real situation under field conditions.

*Varroa* mites remain a significant challenge for honey bee health, and mite control is an essential beekeeping practice. It is therefore important for us to understand the best ways to control *Varroa* levels in colonies while causing minimal harm to honey bees themselves both in terms of direct toxicity and potential interactive effects with other commonly encountered agrochemicals.

### PESTS AND PATHOGENS

Pollinators face a variety of pests and pathogens that can contribute to individual (and colony) stress and declines in managed and wild populations. There is evidence that non-native and commercially-reared bees can increase the risk of pest and pathogen spread (Stout and Morales 2009), including further spread of the pervasive *Varroa* mite in honey bee colonies. Infection of managed species by multiple pathogens, and the resulting interactions between pathogens and other stressors, is thought to be a major contributor to Colony Collapse Disorder (CCD) in the USA (Cox-Foster et al. 2007; Highfield et al. 2009; Le Conte et al. 2010). Climate change can also affect the spread and persistence of pests and pathogens (Le Conte and Navajas 2008; Schweiger et al. 2010). Other stress factors such as land-use change, habitat loss, agrochemical load and colony management practices may also increase pollinator susceptibility to pests and pathogens.

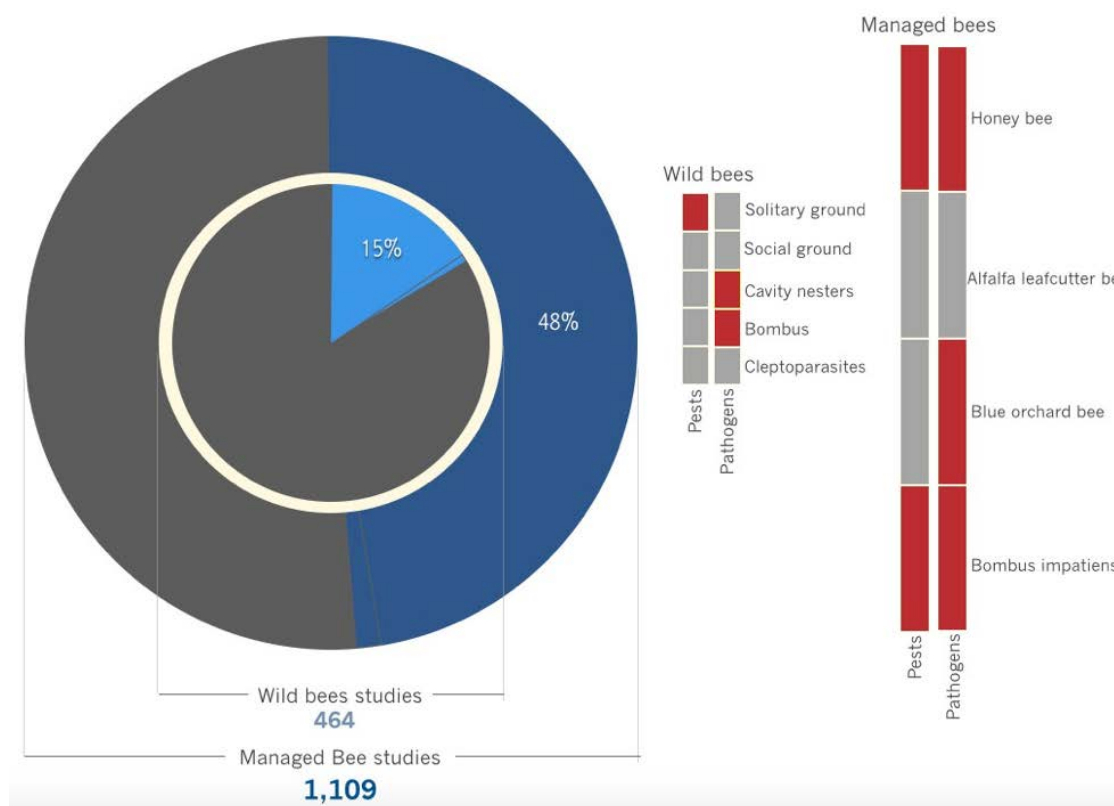
Evidence that widespread transmission of viruses between managed and wild pollinators exists, highlighting the interconnectedness of potential disease pressures within and among pollinator species (Fürst et al. 2014; Graystock et al. 2014; McMahon et al. 2015). This is particularly true for honey bee viruses, as some are known to invade multiple host species (Eyer et al. 2009). Other managed bees can also act as dispersal vectors for parasites and associated diseases leading to infection in wild bee communities.

There is well established evidence that these stressors have a negative impact on honey bee (Desai et al. 2016; Emsen et al. 2015; Guzman-Novoa et al. 2010; Hamiduzzaman et al. 2010; Mattila and Otis 2006a) and bumble bee (managed and wild) health in Ontario (Colla and Packer 2008; Colla et al. 2006; Macfarlane 1976; Otterstatter and Thomson 2008). Pests and pathogens are the most researched for honey bees compared to all other bee species, and an overview of their distribution in Ontario, their severity, and their management solutions is outlined in Table 4. Our literature searches also found speculative evidence for the impacts of these stressors on *O. lignaria*, *M. rotundata* and other wild pollinators.

### **Summary of Evidence**

There has been a great deal of research effort focusing on the impacts of pests and pathogens for managed pollinators, particularly honey bees (Figure 10). As a result there is considerably more evidence on the impacts of pests and pathogens for managed pollinators compared to wild species (although impacts on bumble bees have also received appreciable attention). Several trends are evident in the literature: 1) *Varroa* mites are the largest problem contributing to overwintering loss of all the pests and pathogens affecting honey bees in Ontario. *Varroa* mites directly kill bees by feeding on their haemolymph, but they also indirectly kill them by infecting bees with viruses. The combination of mites and viruses is widely considered to be a major mechanism for global honey bee colony losses. 2) Small hive beetle (*Aethina tumida*) is an emerging problem in Ontario. *B.*

*impatiens* is a potential alternate host species as small hive beetle invades managed bumble bee colonies. 3) Bacterial diseases, fungi and viruses are a recurring issue faced by beekeepers, but the impact of these stress factors on managed pollinator health in Ontario is not fully understood as these diseases are not currently being monitored. 4). Pathogen spillover (e.g. *Nosema* and tracheal mites) from commercially reared populations of *B. impatiens* is an emerging problem facing wild *Bombus* species, particularly in Southern Ontario where greenhouses are most numerous. There is some evidence suggesting potential for interactions between pest or pathogen infection and exposure to agrochemicals (particularly insecticides) for honey bee and bumble bee health. Nothing is currently known about such impacts for these species, or wild pollinators, in Ontario.



**Figure 10.** Pie chart illustrating the percentage of unique relevant studies that investigated the impacts of pests and pathogens on both wild (light blue sector, inner circle) and managed bees (dark blue sector, outer ring). Literature consensus produced on the right hand side demonstrating the impacts of pests and pathogens on wild and managed bees. Green indicates the factor has a positive effect on pollinators, yellow indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory, and red indicates the factor has a negative effect on pollinators. Grey cells in the consensus table represent current knowledge gaps (for more details see page 20).

## Managed Pollinators

### **Parasitic mites**

#### ***Varroa* Mites**

The mite *Varroa destructor* is a parasitic mite that only infests honey bees. The presence of varroa was first reported in Canada in 1989 (McElheran 1990) and is now distributed throughout regions of Ontario where honey bees are kept and found in almost all honey bee colonies (Kozak 2012c). The range of *V. destructor* in the province is expanding, as mites are spreading into Thunder Bay – a site previously uninfested in 2012. A study investigating 408 colonies in six regions of southern Ontario determined *Varroa* is the most significant driver of overwintering losses and reduced bee populations in the province (Guzman-Novoa et al. 2010). Although beekeepers are actively managing their hives, mite levels are constantly rising in colonies (Kozak 2015a). Levels were monitored every year until 2006, when consistent incidence of 95-98% in colonies suggested that *Varroa* was ubiquitous. The seasonal levels reflect the natural life cycle of the pest, beginning lowest in spring and reaching their maximum point in October. Controlling hives with a variety of treatments is essential to prevent colony death, however mites are gaining resistance to several miticides. Resistance of the common treatments coumaphos and fluvalinate are documented at increasing rates each year throughout Ontario. Recent field trials determined fluvalinate is now effective 70-90% of the time, and coumaphos is now only effective 40% of the time when used to treat *Varroa* (Kozak 2015a). Taken together, there is well established evidence that *Varroa* is a significant factor affecting honey bee health in Ontario.

In addition to the morbidity and mortality caused by directly by *Varroa*, there is a strong likelihood that honey bees from *Varroa* infested colonies are infected by viruses carried and transmitted by the mite. *Varroa* has recently been discovered to be a vector for deformed wing virus (DWV), and in most cases the presence of the mite increases virulence (Francis et al. 2013). For instance, workers and drones (males) experimentally infected with DWV alone are usually asymptomatic, and symptoms have never been described in queens. However, a study in Atlantic Canada found that a *Varroa* infestation accompanied with DWV causes intense infections across castes (including queens) demonstrated by the characteristic deformed wing trait (Williams et al. 2009). A study in Italy revealed the collapse of mite-infested colonies were found to occur because of the lethal DWV levels (Annoscia et al. 2012), and bees parasitized by *Varroa* were also infected with DWV almost 100% of the time (Le Conte et al. 2010). Similarly, winter losses in Switzerland have been significantly correlated with DWV and Acute Paralysis Virus (APV) associated with *Varroa* (Berthoud et al. 2010; Dainat et al. 2012). In Ontario, colonies with high *Varroa* levels have been shown to experience more severe viral infections than colonies with low mite levels (Emsen et al. 2015). Taken together, these research findings emphasize the combined interactive effects of *Varroa* and viruses as a main cause of honey bee colony losses, but the relative contribution of the mites and the viruses they transmit are difficult to dissociate. In addition to DWV and APV, research suggests *Varroa* may also be a vector to other viruses, including Sacbrood virus, Israeli Acute Paralysis virus (IAPV) and Kashmir bee virus (KBV) (Le Conte et al. 2010). In addition to determining the role of *Varroa* in overwintering mortality, research in Ontario has also investigated the role of genetics in honey bee resistance. Some honey bee genotypes have been found to be less susceptible to the mite (Guzman-Novoa et al. 2012), with more resistant bees undertaking grooming behaviour more often and with higher

intensity. This behavioural pattern had been previously observed in Africanized bees in Mexico (Arechavaleta-Velasco and Guzman-Novoa 2001) and genes associated with this mechanism of resistance to varroa, have been mapped (Arechavaleta-Velasco et al. 2012). Selecting for mite resistant honey bees may provide additional protection against *Varroa* as the issue of miticide resistance becomes increasingly problematic for mite control. Emsen et al. (2012) suggest that additional, as yet undiscovered, mechanisms besides grooming and hygienic behaviour may contribute to *Varroa* resistance in Ontario.

### Tracheal Mites

The honey bee tracheal mite, *Acarapis woodii*, was first introduced to Canada in the late 1980s and has since spread throughout the country (BCMA 2012). The exact distribution of tracheal mites in Ontario is unknown, but from 2011 they were thought to be in all regions except Thunder Bay (Kozak 2012b). There is some discrepancy about the prevalence of tracheal mites in Ontario. While Canadian apiarist reports document tracheal mite levels in Ontario have increased from 8% colony incidence in 1998 (CAPA 1999) to 60% in 2005 (CAPA 2006), a separate study by Guzman-Novoa et al. (2010) surveyed over 400 colonies in Ontario and found only 6.1% tested positive for tracheal mites. Currently, neither incidence nor prevalence of tracheal mite is regularly monitored in Ontario, but in cases where hives are infested, they tend to die over winter (Guzman-Novoa et al. 2010). The discrepancy in prevalence rates between studies is probably a consequence of smaller sample sizes in the apiarist reports. Despite their contributions to overwintering loss, there is incomplete and conflicting evidence to suggest they increase the likelihood of colony failure during the active bee season. One study found that bees infested with tracheal mites do not experience a reduction in survivorship and foraging ability (Gary and Page 1989); however, more recent work has found that bees infested with both tracheal and *Varroa* mites experience a negative interaction between the two mites in that foraging is significantly reduced compared to colonies infested with either mite species individually (Downey et al. 2000). Tracheal mites may therefore be most destructive to colony health when found in combination with *Varroa*, but more research is needed to verify this interaction. The status of tracheal mites in Canada is similar to the situation in the USA and Europe, where it used to be a more prevalent problem in the 1980s and 1990s but now levels are lower and more manageable (Cobey and Lawrence 1986; Delfinado-Baker 1988; Maki et al. 1987; McMullan 2011; Tarpay et al. 2007; Wilson et al. 1988), likely a consequence of artificial and natural selection which eliminated the most susceptible bee genotypes.

Tracheal mites (*Locustacarus buchneri*) have also been found in commercial bumble bee colonies (Goka et al. 2000), although companies are fairly effective in controlling them (Graystock et al. 2013). The mite feeds and reproduces mainly in the abdominal air sacks of adult queen and worker bees (Yoneda et al. 2008). In Ontario, Colla et al. (2006) found that a greater proportion of bumble bees foraging near commercial greenhouses in southern Ontario were infested with *Locustacarus buchneri* than those caught elsewhere. In southwestern Alberta, Otterstatter and Whidden (2004) also studied parasitism of bumble bees and found that tracheal mite infestations were relatively host-specific, with most host species in the subgenus *Bombus* sensu stricto. Interestingly, this subgenus includes the rusty-patched bumble bee, *Bombus affinis*, a species listed as endangered in Ontario (COSEWIC 2010; Colla 2016). At typical colony infestation levels, *L. buchneri* is not considered to as a major stress factor for natural bumble bee colonies, and bees often appear asymptomatic (Alford 1975; Macfarlane et al. 1995b). However, at high levels, mites damage the host's trachea causing them to become lethargic, cease foraging (Alford

1975) and reduces their lifespan (Otterstatter and Whidden 2004). Although relatively little is known about the degree of morbidity *L. buchneri* mites cause in wild bumble bees, this parasite is considered to be a negative stressor.

**Table 4.** Overview of Pests and Pathogens in Ontario. Adapted from OMAFRA (Kozak 2012): an introduction to honey bee pests and diseases in Ontario.

Category	Species	Distribution	Severity	Management Solutions
<b>Parasitic Mites</b>	Tracheal mites	Widely distributed, exact distribution unknown. Very low prevalence	Moderate to serious	Registered chemical treatments & resistant bee stock
	<i>Varroa</i> mites	Widely distributed, common in most regions	Highly virulent & fatal if not managed	Registered chemical treatments & cultural control
<b>Bacteria</b>	American foulbrood	Widely distributed, less common. Monitored annually	Highly virulent & contagious	Antibiotics, quarantine, and destruction of infected equipment
	European foulbrood	Widely distributed, less common. Monitored annually	Manageable	Manage with antibiotics
<b>Fungi</b>	Chalkbrood	Widely distributed, common. Monitored annually	Usually a minor pest, rarely serious	Manage by requeening
	<i>Nosema apis</i>	Widely distributed, common	May be virulent in winter & spring	Manage with antimicrobials
	<i>Nosema ceranae</i>	Widely distributed, common	Moderate to virulent	Manage with antibiotics & comb replacement
<b>Viruses</b>	Deformed wing virus	Many honey bee viruses are widely distributed. The presences and levels of particular viruses vary	Viruses listed here range from moderate to severe	Although there are no registered treatments specific to viruses, beekeepers may manage virus levels to a certain extent by managing <i>Varroa</i> infestations
	Israeli acute paralysis virus			
	Kashmir bee virus			
	Black Queen cell virus			
	Sacbrood	Sacbrood monitored annually		
<b>Pests</b>	Wax moth	Widely distributed	Pest of colonies	Colony management
	Small hive beetle	Restricted distribution, presently known sites Essex County and Chatham-Kent are under quarantine. monitored annually	Pest of weak colonies and honey stores. Implications for exporting bees to other regions	Colony management, best management practices in the honey extraction facility



## Pests

### Greater and Lesser Wax Moth

There are at least two moth species that are globally distributed and damage honey bee hive combs: the greater (*Galleria melonella*) and lesser (*Achroia grisella*) wax moths. The most common is *G. melonella*. These moth larvae feed on wax, honey and pollen; they affect weak colonies that are unable to get rid of them and cannot protect all the combs in the hive. Stored combs in warehouses are also affected during the warmest months of the year. These pests are the most damaging of all invertebrate pests known to affect honey bees, as they can reduce drawn comb to webbing and debris (Ellis et al. 2013). To the best of our knowledge, no research exists that directly measures the impact of these pests on honey bee health or colony survival. Bees in populated hives will usually eliminate these pests on their own, but under times of stress, wax moth larvae can become a problem. In these cases, they could be treated with *Bacillus thuringiensis* (Ellis and Hayes 2009) although most beekeepers do not use this bio-control method. Management practices to ensure hives are healthy and well populated are the best strategy to deal with wax moths. Empty equipment must be stored at freezing temperatures during the winter (freezing temperatures kill the moths).

### Small Hive Beetle

The small hive beetle (*Aethina tumida*), a native of Southern Africa, is prevalent throughout most parts of Australia (excluding Western Australia and Tasmania: Neumann et al. 2010) and the eastern USA (de Guzman et al. 2010; Spiewok et al. 2008), where it is causing significant colony losses. In 2014, the beetle entered Europe where it poses as a significant threat to honey bee colony health (Mutinelli et al. 2014). Adults beetles mate inside hives and females lay eggs in crevices or combs. Larvae feed on honey and pollen and eventually crawl out of the hive and pupate in the soil. Adults emerge and return to hives. Honey of affected colonies ferments and spills in the hive; its odour causes bees to abscond. The small hive beetle was first reported in Canada in 2006 (Kozak, 2010b) and was found in Essex County Ontario in 2010 (introduced from the USA: Kozak 2010a). Colonies are monitored annually for the presence of small hive beetle and the current target sites with higher risk of infestation are counties along the Saint Lawrence River, those closest to the USA border (Lambton County, Niagara County, and Chatham-Kent County) and also closest to known regions of previous infestations (Kozak 2014b). Incidence reports had remained stable from 2011 to 2013, with annual monitoring identifying six sites infested with small hive beetles in these years. Only one site was reported as infested in summer 2014, located in Niagara County (Kozak 2015b). All hives were destroyed and Essex County and the Chatham-Kent County remain quarantined (Kozak 2015b). Ongoing colony monitoring and early response has successfully contained the small hive beetle to these regions, and these measures will need to remain in place to prevent further spread.

Bumble bee species are also susceptible to small hive beetle in North America. This beetle has been reported to enter and lay eggs inside *B. impatiens* nests (Hoffmann et al. 2008). In a laboratory study conducted in the USA, Ambrose et al. (2000) artificially infested *Bombus* colonies with small hive beetles, which proved extremely virulent. On average 14 days after infestation, colonies contained 23 live and 172 dead bees (of which 33 were intact). 24 days after infestation, colonies contained no live bees. In Europe, infestation of bumble bee colonies by small hive beetles was observed in a controlled field setting by infested apiaries (Spiewok and Neumann 2006). They found that within 8 weeks all 10

colonies were infested with adult small hive beetles. It is currently unknown if small hive beetles are able to invade natural, ground-nesting and commercial colonies in field or greenhouse settings. However, given the rapid spread of small hive beetle in US honey bee apiaries, it is plausible that Ontario bumble bee colonies could be susceptible.

### ***Crithidia bombi* in Bumble Bees**

There is evidence of pathogen spillover of *C. bombi* from commercial bumble bee colonies to wild bees in Ontario (Colla et al. 2006; Otterstatter and Thomson 2008). Using a spatially explicit model, and subsequent field trials, Otterstatter and Thomson (2008) found that commercial hives could infect up to 20% of wild *Bombus* within 2 km of greenhouses during the first three months of pathogen spillover. Colla et al. (2006) also found that *Bombus* collected near greenhouses were more frequently infected with *C. bombi* than at sites further away. Although commercial bumble bees are typically placed inside greenhouses it is virtually impossible to prevent some escapes through vents or doors. As such potential spillover of *C. bombi* from commercial colonies is likely to occur from early spring to late fall, which overlaps with the entire flight period of all wild bees. Impacts of *C. bombi* on wild and managed bumble bees are well characterized in Europe (e.g. Brown et al. 2003; Imhoof and Schmid-Hempel 1999; Sadd and Barribeau 2013) and could be exacerbated by pesticide exposure. Limited evidence from two studies from Europe reported a significant interaction between neonicotinoid exposure and *C. bombi* infection on mother queen survival (Fauser-Misslin et al. 2014), but no interaction was found between infection and pyrethroid exposure (Baron et al. 2014).

## **Bacterial Diseases**

### **American foulbrood**

American foulbrood (*Paenibacillus larvae* ssp. *larvae*) is a highly contagious bacterial disease that causes old larvae and pupae to decay. American foulbrood is considered the most serious disease of honey bees. Spores of *P. larvae* are resistant to antibiotics and many remain viable for many years. This disease has a worldwide distribution and has been reported from honey bee colonies throughout Ontario. It is a notifiable disease in Ontario, and infected colonies must be destroyed by fire. Colony incidence is reported every year by the Ontario Ministry of Agriculture, Food and Rural Affairs (Table 5). Average colony incidence over the past fourteen reported years runs at 2.3%, and has never exceeded 4.3% (Kozak 2014b). These comparatively low levels from apiary inspections reflect successful hive management practices, although these figures do not always agree with incidence levels reported by beekeepers. For example, in 2001 35% of beekeepers reported having hives infected with American foulbrood, yet the inspectors documented a colony incidence of 2.3% (CAPA 2002). American foulbrood is typically treated with oxytetracycline to prevent infestation (Kozak 2012a). Resistance to this antibiotic has been documented outside the province, but no resistance has yet been reported in Ontario.

### **European Foulbrood**

European foulbrood (*Melissococcus plutonius*) is an infectious disease of honey bees that causes larvae and pupae to decay. The incidence of infected colonies in Ontario is low, averaging 0.24% over the past thirteen reported years, and like American foulbrood, it continues to be monitored every year (Kozak 2014b: Table 5). We found no peer-reviewed articles examining the negative effects of European foulbrood on colony health

or survival. Monitoring reports indicate that this bacterial disease has a relatively minor to negligible impact on honey bee health in Ontario. When detected, colonies are treated with the antibiotic oxytetracycline.

**Table 5.** Incidences of diseased honey bee colonies in Ontario. Data presented in unshaded cells is from annual provincial apiarist inspections (no data were collected for these long term datasets in 2009 as no provincial apiarist was in post). Information on virus infection levels for 2009 was collected by Desai et al. (2016), who examined 10 randomly selected hives in Ontario (grey shaded cells).

Diseases	Disease Colony Incidence (%)															
	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
AFB	3.6	2.8	2.3	2.7	2.96	1.7	1.9	1.94	-	3.2	4.3	-	0.5	0.7	2.5	1.3
EFB	0	0	0	1.1	0.01	-	1.6	0.12	-	0.02	0.06	-	0.02	0.01	0.1	0.05
Chalkbrood	2.6	3	2.5	3	4	2.5	3.8	4.16	-	5.0	4.8	-	1.8	3.6	5.6	1.0
Sacbrood	0.5	1	1	-	0.35	0.3	1.05	0.35	-	0.05	0.67	0	0.4	0.01	1.4	0.5
ABPV	-	-	-	-	-	-	-	-	-	-	-	20	-	-	-	-
BQCV	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-
CBPV	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-	-
DWV	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-
IAPV	-	-	-	-	-	-	-	-	-	-	-	70	-	-	-	-
KBV	-	-	-	-	-	-	-	-	-	-	-	30	-	-	-	-
Tracheal Mite	8	15	40	45	45	76	45	60	-	-	-	-	-	-	-	-
Varroa Mite	55	82	95	95	95	-	98	95	-	-	-	-	-	-	-	-

## Fungal Diseases

### Chalkbrood

There are two fungal diseases in Ontario that affect honey bees, chalkbrood (*Ascosphaera apis*) and *Nosema* (both *Nosema apis* and *Nosema ceranae*). Chalkbrood exclusively affects brood and is often commonly identified in Ontarian honey bees, averaging 3.4% colony incidence over the past fourteen reported years, with the highest reported levels of 5.6% (Kozak 2014b). Despite being one of the most prevalent monitored diseases for Ontarian honey bees (Table 5), chalkbrood can be managed and is not considered a serious fungal disease. Colonies are more likely to develop chalkbrood if they are experiencing nutritional stress (Flores et al. 2005) and/or have poor hive ventilation (i.e., high humidity and cooler in-hive temperatures: Flores et al. 1996). There is no recommended chemical treatment for chalkbrood, but requeening infected hives is a common management strategy (Sanford 1987).

The ALCB (*M. rotundata*) is highly susceptible to chalkbrood infection, but chalkbrood in ALCB is caused by a different fungus than in honey bee larvae (*Ascosphaera aggregate* Skou: Goerzen et al. 1992). This disease has also caused significant mortality in *M. rotundata* populations in the northwestern USA since 1972, and was found throughout Western Canada in the early 1980s. It is not known precisely when the disease was introduced in Ontario but it is likely that it arrived at approximately the same time (early 1980s) or shortly thereafter. Reports of *A. aggregate* from wild populations of *Megachile relativa* (Cresson) in Ontario, indicates transmission to wild populations (Goerzen et al. 1990, 1995). Annual surveys of *M. rotundata* populations from alfalfa seed producing areas are undertaken in Saskatchewan to assist in *A. aggregate* detection.

An additional chalkbrood fungus, *Ascosphaera torchioi* (Youssef et al. 1985), infects the managed BOB, *Osmia lignaria propinqua* Cresson (Torchio 1992), in Ontario. Infection rates by *A. torchioi* vary between 0.36% (Torchio 1992) and 57% (Rust and Torchio 1991) in US studies. Levels of *A. torchioi* are not currently being monitored in Ontario and information about their transmission potential to wild bees is limited. However, Youssef et al. (1985) confirmed that an undescribed *Ascosphaera* species found in *O. lignaria* was not found in other host bee species, providing a strong indication that *Ascosphaera* species are restricted to one or very few closely related hosts.

### ***Nosema apis* and *Nosema ceranae***

*Nosema* spp. cause an infection of the digestive tract of adult honey bees worldwide. A study examining *Nosema* levels in 233 hives in southern Ontario found 86% were infected (Lacey 2014). Low levels of *Nosema* infection do not seem to have observable impacts on colony health, but infection levels at 1.3-3.0 million spores per bee significantly reduce hive populations (OBA Tech-Transfer Program 2013).

*Nosema ceranae* is often reported as more virulent and induces higher bee mortality than *Nosema apis* in some countries (Antunez et al. 2009; Paxton et al. 2007), however, this is not always the case in other countries (Forsgren and Fries 2010). *Nosema apis* has been infecting *A. mellifera* worldwide for over 100 years (Copley et al. 2012), whereas *N. ceranae* has arguably recently switched hosts from the Asian honey bee *Apis cerana* to infect *A. mellifera* (Traver and Fell 2015). *Nosema ceranae* was first detected in Canada in the Maritimes in 2006 (Williams et al. 2008) and shortly after was found to be distributed throughout all provinces of Canada (Currie et al. 2010; Copley et al. 2012). Currently, *N. ceranae* is the more prevalent of the two *Nosema* species in Ontario (Currie et al. 2010; Lacey 2014), infecting over 90% of *Nosema*-infected bee samples (Guzman-Novoa, pers. comm.). These observations are similar to patterns in Quebec (Copley et al. 2012), but different to Alberta, where *N. apis* is found at higher rates (Currie et al. 2010). The predominant *Nosema* species is also highly variable by region across the USA (Szalanski et al. 2013; vanEngelsdorp et al. 2009) and Europe (Bollan et al. 2013; Forsgren and Fries 2010, 2013, Gisder and Genersch 2013; Muz et al. 2010), perhaps as a function of climate and date of *N. ceranae* arrival. In addition, a recent study from the USA examined the prevalence and intensity of *N. ceranae* infection in bees from various age cohorts in a colony and showed that both prevalence and intensity of *N. ceranae* infection is significantly influenced by honey bee age (Jack et al. 2016). There is evidence from outside Ontario of interactive effects on honey bees when exposed to *N. ceranae* and insecticides (Alaux et al. 2010a; Aufauvre et al. 2012; Doublet et al. 2014; Pettis et al. 2012; Vidau et al. 2011) and/or *N. ceranae* and Black Queen Cell virus (Doublet et al. 2014). In these studies infection with *N. ceranae* could exacerbate the toxic effects of exposure to either neonicotinoid insecticides or fipronil, or insecticide exposure could increase the likelihood and/or intensity of a *N. ceranae* infection. More research is needed to elucidate the full extent of these, and other, pesticide-parasite interactions as in reality bees are typically exposed to multiple pesticides and diseases/pathogens under field conditions. *Nosema* is treated with the antibiotic fumagillin and no alternative products exist for its control. Fumigillin applications are associated with a risk of hive product contamination (e.g. honey) and also development of resistance to this treatment. Alternative control methods are needed.

*Nosema bombi* is a well-documented fungal disease that mainly affects bumble bees. It is known to infect a number of bumble bee species at various rates, and has a range of

deleterious effects on its hosts (Otti and Schmid-Hempel 2007). *Nosema bombi* is found in the hind gut and infects all castes when they ingest cells (Yourth and Schmid-Hempel 2006). Infections can be picked up within the nest or from flowers contaminated by an infected bee (Durrer and Schmid-Hempel 1994). As with *C. bombi*, *N. bombi* is thought to spread to wild bee populations through pathogen spillover from commercial *Bombus* populations, as both of these pathogens are common in commercial bees (Otterstatter et al. 2005; Sachman-Ruiz et al. 2015). Colla and colleagues (2006) found that 15% of bumble bees collected within close proximity to greenhouses in Leamington, Ontario were infected by *N. bombi*. Furthermore, they found that intestinal pathogens are rare (<4%) at sites distant to commercial greenhouses. Thus spillover of pathogens from commercial to wild populations near greenhouses is the most likely cause of this pattern.

## Viruses

To date only nine of the viruses detailed in Table 6 have been detected in Ontario, though it is noteworthy that comprehensive testing for the appearance of other viruses has only recently started. It is possible that many other viruses are infecting honey bees in this province based on their distribution throughout the USA and Europe, and their association with ubiquitous *Varroa* mites (Chen et al. 2014; Nielsen et al. 2008; Nordström et al. 1999; Tapaszi et al. 2010). Before 2014, the only virus that was monitored in Ontario was sacbrood because it is easy to identify upon visual inspection. Sacbrood levels have remained low in Ontario, an average infection rate of 0.5% over the past fourteen reported years (Kozak 2014b). Desai et al. (2016) monitored virus levels in ten randomly selected apiaries in Ontario in 2009 and detected no infections with either sacbrood or chronic bee paralysis virus (CBPV), but 20% of bees were infected with acute bee paralysis virus (ABPV), 30% with KBV, and 70% with IAPV. Furthermore, all bees tested were infected with black queen cell virus (BQCV) and DWV. Monitoring of DWV, KBV, BQCV, ABPV, CBPV, and IAPV in addition to sacbrood began in the summer of 2014, but the inspections will not be routine and the first analysis is yet to be released (Kozak, pers. comm.). In contrast to Ontario, the US screens honey bee colonies for viruses every year. The USA National Honey Bee Pests and Diseases Survey have reported the most common viruses to be ABPV and BQCV, with these viruses both present in over 80% of colony samples (Rennich et al. 2013). The variation in infection status reported in different years and locations underline the value of establishing comprehensive virus testing in Ontario, as current monitoring is unlikely to reflect the incidence and prevalence of virus infections in the province. The logistics of sample collecting and the cost of laboratory analysis is the main obstacle in conducting such testing (Kozak, pers. comm.). Because there are no treatments that target viruses directly, the current beekeeping recommendation to control viruses is to manage *Varroa* mites and *Nosema* with which viral infections are associated.

Fürst et al. (2014) examined the potential for honey bee pathogens, particularly viruses, to cross host-genus boundaries. Their work focused on the infectivity of the DWV complex, including the co-occurring *Varroa* destructor virus (VDV), and found that honey bees are in fact widespread infectious agents of these pathogens. Furthermore, DWV and *Nosema ceranae* infections in honey bees and bumble bees are inter-linked as their infections are caused by the same DWV strains (Fürst et al. 2014). Bailey and Gibbs (1964) also reported a DWV-honey bee virus strain in two bumble bee species (*Bombus terrestris* and *B. pascuorum*) in Europe. Other reports of so-called “honey bee viruses” have been reported from non-*Apis* pollinator species. In the USA, Singh et al. (2010) detected a number of viruses assumed to be honey bee specific (DWV, BQCV, SBV, KBV, IAPV) in 11 non-*Apis* Hymenoptera on flowering plants near honey bee apiaries - including three

bumble bee species (*Bombus impatiens*, *Bombus vagans* and *Bombus ternarius*), the eastern carpenter bee (*Xylocopa virginica*), the small carpenter bee (*Ceratina dupla*), the sweat bee (*Augochlora pura*), mining bees (*Andrena spp*), the yellow jacket (*Vespula vulgaris*), paper wasps (*Polistes metricus* and *Polistes fuscatus*) and sand wasps (*Bembix spp.*) (Singh et al. 2010). Similar viruses have been reported from wild bumble bee species in Europe (ABPV, BQCV, CBPV, DWV, SBPV, SBV: McMahon et al. 2015) and commercial *B. impatiens* from greenhouses in Mexico (ABPV, CBPV, DWV, IAPV, KBV: Sachman-Ruiz et al. 2015). There is well-documented evidence that current and ongoing risks of pathogen transmission between managed and wild pollinator species exists globally. Evidence specifically from Ontario is less well established in pollinator taxa other than bumble bees.

### Suggestions

A more comprehensive annual monitoring program is needed to fully evaluate the distribution and prevalence of honey bee pests and pathogens in Ontario. Currently, American foulbrood, European foulbrood, chalkbrood and sacbrood are the only diseases that are regularly screened and documented. The prevalence and distribution of *Nosema* spp., many viruses, and their interactions with *Varroa* mites, are poorly known in the province. Regularly identifying disease and virus prevalence will be important not only for determining their potential impacts on local bee populations, but also for documenting and measuring the success of health control measures as well as ensuring the health status of managed bees imported to, and exported from, Ontario. Because many of these viruses are typically asymptomatic in healthy honey bee colonies, this will help prevent further introduction of non-native pests and pathogens.

Detailed knowledge about the prevalence and infection levels (load) are still lacking for the vast majority of pests and pathogens in wild bees. This represents a significant gap in understanding, particularly given the prominent role that viruses in particular are believed to play in causing pollinator declines. Research to examine whether pest or pathogen infections are likely to increase the susceptibility of managed or wild pollinators to agrochemical exposure (or other environmental stress factors) would be an important contribution to knowledge of this emerging topic in the province and around the world.

**Table 6.** Honey bee viruses and their symptoms (adapted from Kevan et al. 2006).

Virus	Symptoms	Presence in Ontario	Reference
Israeli Acute Paralysis Virus IAPC	Virus attacks all stages and castes of honey bees. Adults exhibit trembling wings and progressive paralysis. IAPV is the most consistent indicator of colony collapse disorder in the USA		Emsen et al. (2015), Kozak (2012)
Black Queen Cell Virus	BQCV affects queen prepupae and pupae sealed in cells. They become pale, and then darken, staining the cell. Mostly in association with <i>Nosema apis</i>		Emsen et al. (2015), Kozak (2012)
Deformed Wing Virus	DWV affects pupae and adults. Wing and abdominal deformities, cognitive impairments, and a very reduced lifespan. Symptoms usually only occur when the hive is infested with <i>Varroa</i>		Emsen et al. (2015), Kozak (2012)
Kashmir Bee Virus	No prescribed set of symptoms for KBV. Hives appear weak, there are increasing numbers of dead bees in and in front of the hive. Bees may be trembling, partially hairless, dark, opaque, or greasy		Emsen et al. (2015), Kozak (2012)
Sacbrood Virus	Affects the developing brood. Larvae change from white to gray to black, and eventually die. Head development is impaired. When larvae removed from cells they appear to be a sac filled with water		OMAFRA 2007, 2012 2013, Kozak (2012)
Chronic Bee Paralysis Virus	Adults experience trembling of the body and wings. Bees may become hairless and darker in colour and are often nibbled on by other bees in the hive.	Unknown (present USA and Europe)	EURL (2013), USDA (2013)
Acute Bee Paralysis Virus	Kills larvae, pupae, and adults only in association with <i>Varroa</i> , otherwise bees seem Healthy.	Unknown (present USA and Europe)	USDA 2013, de Miranda et al. (2010)
Cloudy Wing Virus	Affects adult bees. Main symptom is opaque wings, but this is not always observed.	Unknown (present Europe)	Carreck et al. (2010)
Kakugo Virus	A subtype of deformed wing virus. The main symptom is increased aggressiveness	Unknown (present USA)	Bromenshenk et al. (2010)
Slow Bee Paralysis Virus	Infects larvae, pupae, and adults, but only adults show symptoms. Main symptom is paralysis in the front two legs of adult bees and death within a few days.	Unknown (present USA and Europe)	USDA (2013), Bailey and Woods (1974)
Lake Sinai Virus	No prescribed set of symptoms	Unknown (present USA and Europe)	USDA (2013), Cepero et al. (2014)
Arkansas Bee Virus	No prescribed set of symptoms	Unknown (present USA)	Bailey and Woods (1974)
Iridescent Virus	No prescribed set of symptoms	Unknown (present USA)	Bromenshenk et al. (2010)

<i>Varroa Destructor</i> Virus 1	No prescribed set of symptoms	Unknown (present USA)	Bromenshenk et al. (2010)
Filamentous Virus	Bees are unable to fly and are seen crawling. Under a microscope hemolymph appears milky	Unknown (present USA and Europe)	Bailey and Ball (1991), Clark (1977)
Bee Virus X and Bee Virus Y	Infects adults. Asymptomatic but is sometimes associated with dysentery	Unknown (present Europe)	Bailey and Woods (1974), Bailey et al. (1980)

## MANAGEMENT PRACTICES

At a time where pollinator declines are becoming increasingly widespread, investigating how pollinators respond to management practices such as restoration and habitat management is vital for pollinator conservation efforts.

The Millennium Ecosystem Assessment (MEA) report indicates that across 14 biomes presently 50% of habitats have been degraded and most are used for human use (MEA 2005). Some ecosystems have been degraded to such a degree that the survival of the ecosystem services they provide are now in jeopardy (Kearns et al. 1998). Furthermore, it has been estimated that over the next couple of decades millions of plant and animal species will go extinct due to the way we exploit their ecosystems.

An understudied stress factor to pollinators is the influence of humans on managed and wild species. Human management of land and of pollinators themselves can affect bee health in positive and negative ways. For example, the agricultural practice of the large-scale production of a single crop may affect bee abundance and nutrition negatively by reducing the amount of natural habitat for foraging or nesting sites (Vanbergen 2014). Yet, planting or restoring natural habitats alongside these monoculture fields could impact bees positively. In this section four management practices are outlined and the evidence to support them is discussed: invasive species, land management, restoration, and bee management.

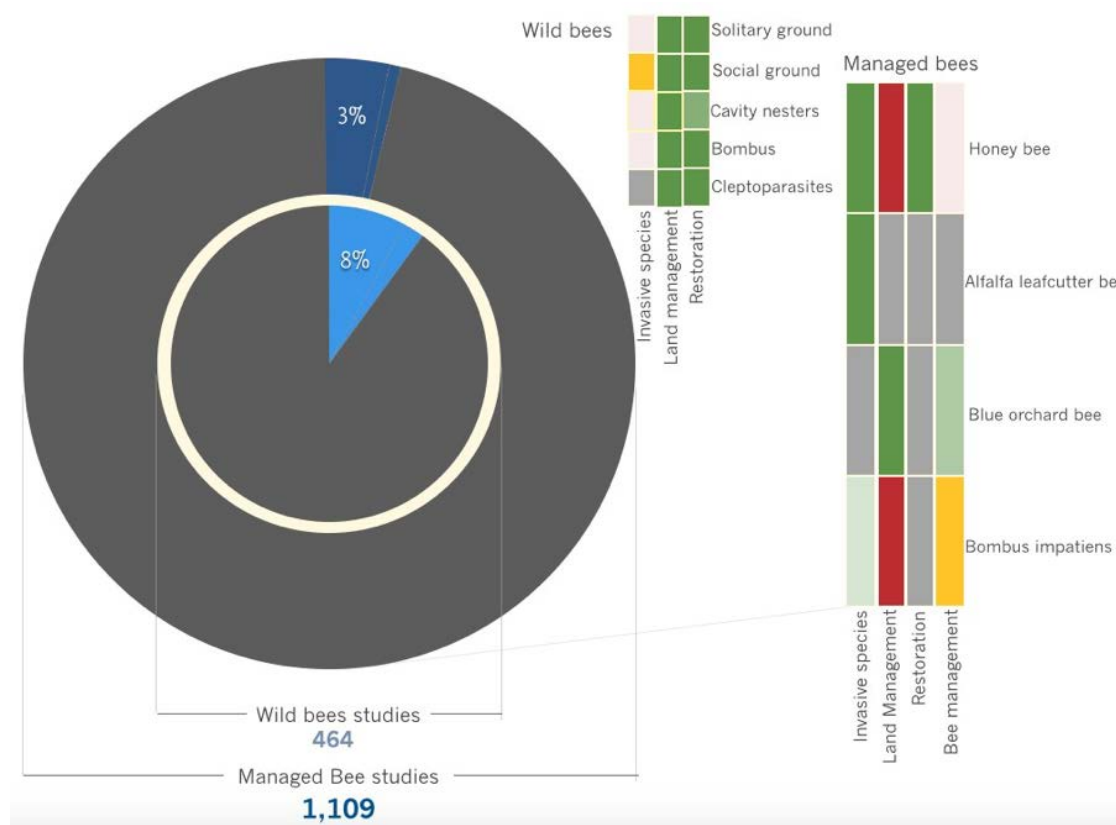
### Summary of Evidence

Overall, studies on management practices tend to focus on those that have a negative effect on bee health (Figure 11). The only evidence that examines the impact of invasive species on honey bees in Ontario are *Varroa* mites and small hive beetles (summarized in the Pests and Pathogens section of this report). Studies examining the effect of land management on honey bees focus on the role of monoculture on colony survival and health. There is conflicting evidence from field and laboratory studies that monoculture negatively affects honey bees, where the outcome depends on the crop used and the initial health status of the bees. Splitting and transporting bees to monoculture fields using migratory beekeeping practices is emerging as a significant source of stress for honey bees. Supplementing hives with pollen and sucrose syrup to alleviate nutritional deficiencies can be beneficial for honey bee health, but the benefit is dependent on the quality of supplements used. Research on managed solitary bee species has been focused on the ideal storage conditions to enhance overwintering success and timing emergence with crop blooms. Keeping other managed bees is relatively low maintenance, but pests and pathogens must be monitored and prevented from spilling over into native bee communities.



There is limited evidence that agricultural practices, such as conserving natural land with native flowers close to cropland, are beneficial for honey bee visitation. However, there is well established evidence that planting and maintaining native flower patches close to agricultural fields as a restoration practice increases both managed and wild pollinator species richness and diversity. The presence of other wild bee species in a field also improves honey bee pollinator efficiency.

There is well established global evidence indicating that examining changes in functional guilds provides a deeper understanding of how pollinator communities respond to management practices.



**Figure 11.** Pie chart illustrating the percentage of unique relevant studies that investigated the impacts of management practices on both wild (light blue sector, inner circle) and managed bees (dark blue sector, outer ring). Literature consensus produced on the right hand side demonstrating the impacts of management practices on wild and managed bees. Green indicates the factor has a positive effect on pollinators, yellow indicates the effect is either neutral for pollinators, or the evidence of effects is contradictory, and red indicates the factor has a negative effect on pollinators. Grey cells in the consensus table represent current knowledge gaps (for more details see page 20).

## Managed Pollinators

### **Invasive Species on Honey Bees**

Currently, the invasive species that impact honey bees in Ontario are *Varroa* mites, small hive beetles, tracheal mites, and *Nosema ceranae*. *Varroa* mites are originally from Asia where they infest the Asian honey bee *Apis cerana*. Since their introduction to Europe and North America, *Varroa* mites have spread to nearly every managed honey bee hive. Likewise, *N. ceranae* may be also from Asia and seems to have made this same host transition to *A. mellifera* (Traver and Fell 2015). Small hive beetles are native to South Africa and have been found to infest bee hives in isolated regions of Ontario. Their spread is currently being prevented through active quarantine of affected bee yards. It is uncertain where tracheal mites originate from, but they were first described in Europe (Woodward and Quinn 2011). The evidence of these invasive species' effects on honey bee health is outlined on page 81. There have not yet been studies that examine the effects of invasive species on other managed bees.

### **Land Management**

#### **Monoculture**

There are no Ontarian studies that examine the effects of monoculture on honey bee health. There is limited conflicting evidence in the form of one Canadian study suggesting that pollinating large fields of monoculture crop results in nutritional stress for honey bees. Girard et al. (2012) measured brood development in colonies after pollination services to monoculture fields of blueberries and cranberries in Quebec. Honey bees pollinate blueberries in June and then the same colonies are shipped to pollinate cranberries in July and August. The authors found that colonies suffered from low brood development significantly more after the monoculture blueberry pollination period than when bees were allowed to pollinate mixed croplands or wild fields. After pollinating cranberries however, bees were able to recover from the low brood development and produced the same amount of brood as the control sites by the end of the season. This study suggests that some crops may illicit deficiencies more than others, and honey bees are able to recover from these effects if given the right environment.

Honey bee cage experiments conducted in the USA and Europe provide further conflicting evidence that monocultural diets affect bee health in general. A European study compared immune responses of bees that fed on monofloral pollen patties to those that fed on polyfloral pollen patties. Immune responses such as phenoloxidase activity, fat body content, and glucose oxidase activity were measured. Bees that ate monofloral patties had significantly lower glucose oxidase activity, which is involved in sterilizing brood food and honey and is therefore a measure of social immunity. However, there were no differences in other variables, such as phenoloxidase activity or fat body content, between groups (Alaux et al. 2010b). Nutritional stress due by monocultures may depend on the crop itself, as some flowers inherently contain pollen with more amino acids and higher protein levels (Huang 2012). A US study found honey bees that fed exclusively on sunflower or sesame pollen experienced significantly higher mortality rates than honey bees that fed on polyfloral pollen (Schmidt et al. 1995), however, bees that fed on rape pollen lived just as long as those that fed on polyfloral pollen. Conversely, Di Pasquale et al. (2013) investigated the effects of diet diversity on the physiology of nurse bees and found that there was no difference in physiology or survival of healthy nurses fed

monofloral pollen versus polyfloral pollen diets. However, these bees were infected with *Nosema ceranae*, those that ate polyfloral diets survived longer than those eating monofloral diets. Overall, these data suggest that the practice of monoculturing negatively affects honey bee health, but whether or not these effects are substantial depends on the type of crop and the original health status of the bees. It is more likely that nutritional stress from monoculture interacts with other stress factors to negatively impact bees to cause obvious signs of colony decline.

### **Agricultural Management**

Besides monoculture, agricultural management practices such as allowing natural habitat to remain near or between agricultural fields and managing which pollinators are used for crops have been little studied. There are no studies in Ontario or Canada that examine these agricultural practices for honey bees. There is limited and conflicting evidence with regards to the effect of natural habitat distance from agricultural fields on honey bee populations. Agricultural practices that are mindful of pollinator habitat have demonstrated their ability to promote honey bee populations in some studies. For example, a European study compared hay agricultural practices that reduce or delay mowing (Buri et al. 2014). Results from this study reported higher abundance of honey bees and wild bees were found in fields that had uncut refuges compared to fields without these features. However, a meta-analysis reported negligible effects of natural habitat isolation on crop flower visits (Garibaldi et al. 2011). These authors noted that 27 out of 29 studies included in their meta-analysis were cropland located within 2 km of natural fields, and with a honey bee foraging range of up to 15 km, these bees were likely able to access natural flowers. Large-scale studies that keep cropland associated with natural land distinct from cropland without natural land are needed to truly uncover the effects of agricultural management practices.

Increasing the pollination efficiency of honey bees for agriculture can be accomplished by encouraging or introducing other wild bee species to an area. The presence of wild bees in an almond orchard was found to increase the individual pollinating efficiency of honey bees and resulted in a greater fruit set compared to an orchard that was pollinated by honey bees alone (Brittain et al. 2013b). The change in foraging behaviour is likely due to the sense of interspecies competition honey bees detect when seeing other bees forage on the same resources.

Agricultural managed practices are also being researched in Canada for the managed bee *O. lignaria*. This bee is used for pollinating fruit trees, which bloom in spring in Ontario. Managing nesting sites near dense orchards allows farmers to have pollination services of these trees in the spring. However, after the spring bloom of orchard trees bees could face a food shortage if there are not other flowers timed to bloom immediately afterwards. A good management practice would be to plant attractive blooming flowers to sustain bees during the summer months. Sheffield et al. (2012) examined other flowers that overlap in and exceed the flowering period of orchard flowers and found bigleaf lupine (*Lupinus polyphyllus* Lindl.) to be a good candidate. Managed bees with access to these flowers were able to sustain their populations throughout the season. Plants native to Ontario should be researched to find similarly attractive species with which to sustain managed bees.

Managed *B. impatiens* tend to escape greenhouses through ventilation systems, providing a potential route of pathogen spillover to wild bees. Management practices to reduce

bumble bees escape include changing greenhouse covering materials. An Ontario study found the most effective coverings that increased both pollination activity and reduced bee escape were those that transmit high levels of UV light (Morandin et al. 2001a). *Bombus* also shows high levels of drifting between colonies in greenhouses. A Canadian study found that placing symbols near nesting boxes to help orient bumble bees does not reduce drift between colonies, but it does help to shorten foraging times and increase rate of pollen collection (Birmingham and Winston 2004).

### **Habitat Restoration and Honey Bees**

Studies examining land restoration techniques to improve honey bee populations examine both wild and managed honey bees. It is well established that planting native flower strips or conserving natural patches near intensely managed agricultural areas increases honey bee abundance (Benelli et al. 2014; Carvalheiro et al. 2011, 2012). These restoration land strips serve as an additional food source for bees when they are faced with deficiencies from certain management practices (i.e. monoculture pollination or low quality food supplements).

### **Bee Management**

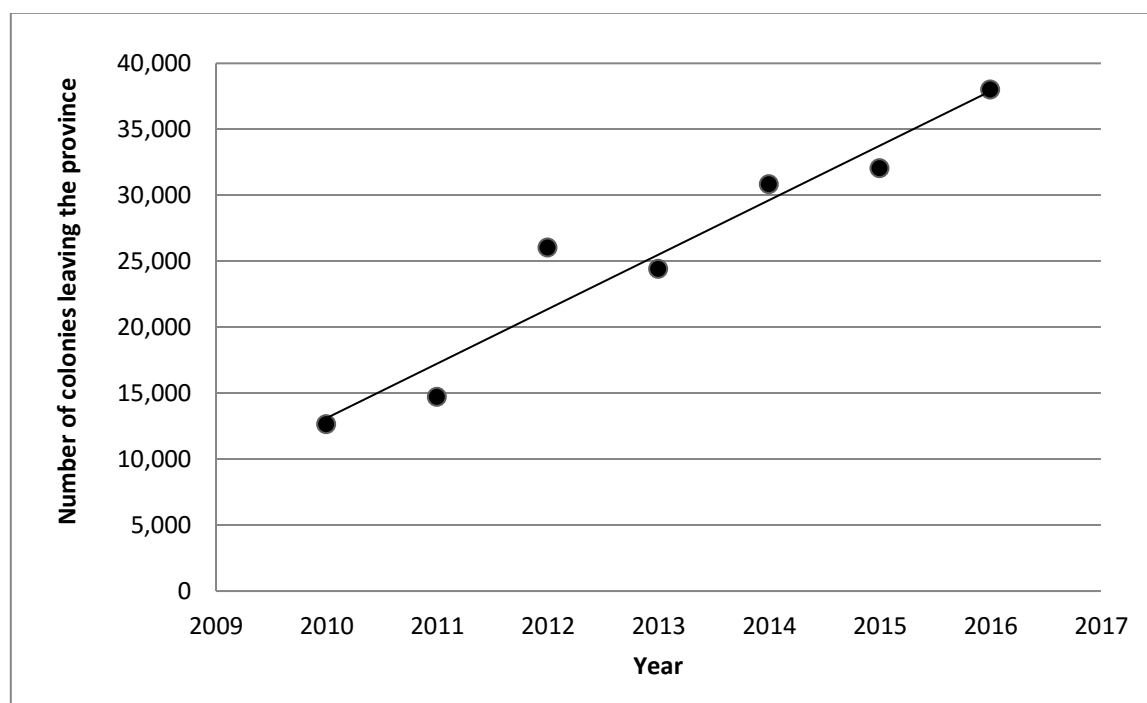
#### **Migratory Beekeeping**

Beekeepers in Ontario make their living by selling honey and providing pollination services. Crop farmers can rent hives to place near their crops during peak pollination times. The need for pollination services is increasing globally (Aizen and Harder 2009). The number of honey bee hives leaving the province to participate in pollination services is increasing (Figure 12), and reached 39% of all managed hives in Ontario (Kozak 2015a, 2016). Some crops have a very narrow window for peak pollination of a few days, requiring hundreds to thousands of hives to be contracted. It is common for hives to be exported from Ontario to assist in crop pollination in canola on the Prairies and blueberries and cranberries in Quebec and the Maritimes (CAPA 2000). Northern Ontario is expected to be an emerging blueberry region, soon requiring even more pollination services than before (Kozak 2015a).

The practice of ‘migratory beekeeping’ has been assumed to induce stress for honey bees (Kevan et al. 2007). We found one US study that compared bees from commercial and experimental migratory beekeeping operations to those from stationary colonies to quantify effects on lifespan, colony health and productivity, and levels of oxidative damage for individual bees (Simone-Finstrom et al. 2016). This study showed a significant decrease in lifespan of migratory adult workers relative to non-migratory bees. More than 400 hives are packed close together on transportation trucks where they are exposed to temperature fluctuations, vibrations, and confinement for days at a time. Once hives arrive at pollination sites, these are usually monoculture fields. Nutritional deficiencies experienced from monoculture, interactions with potential pests and pathogens from bees of other nearby hives, and potential exposure to pesticides applied to the crops may further exacerbate stress. Indeed, colonies in the USA used for migratory beekeeping have viruses at higher rates than stationary colonies (Welch et al. 2009; vanEngelsdorp et al. 2013) and were reported to have the highest incidence of Colony Collapse Disorder (Johnson 2010). At this time, there are no studies in Ontario that examine the effects of transportation stress on honey bees.

Alternative treatment techniques are beginning to be developed to reduce pest loads during transportation. For example, strains of Varroa-resistant bees are just as effective (and sometimes more effective) at reducing mite loads during migratory beekeeping (Danka et al. 2012). These studies together provide limited evidence that transportation is stressful to honey bees. Evidence from large-scale studies comparing several aspects of migratory beekeeping to stationary hives is warranted. In addition to the above, there is empirical evidence from beekeepers that splitting hives to make more pollinating units to rent may lead to weak populations in the fall, which in turn results in higher rates of winter colony mortality.

*Osmia lignaria* are managed in static boxes on orchard sites. Efforts to move boxes from crop-to-crop have been undertaken, but without much success to date. In the USA, a study showed that bees are unable to orient themselves to relocate their nesting sites when they are moved within the same orchard or to a new orchard (Torchio 1991). However, when nesting boxes were on large trailer-shelters, 85% of bees were able to find their nests after they were moved. Although migratory beekeeping will likely never be implemented for *Osmia*, some small-scale transportation seems possible with limited stress effects.



**Figure 12.** The number of honey bee colonies leaving Ontario for pollination services during the period 2010–2016 (data from Kozak 2015a, 2016).

### Nutritional Supplementation

In Ontario, beekeepers supplement honey bees with sugar syrup and pollen substitutes to offset nutritional deficiencies caused by pollinating monoculture crops, honey harvesting and overwintering. In general, there is limited but established evidence that honey bees supplemented with sugar syrup and pollen substitutes are improved in some respects compared with bees that do not receive supplements. Overall, pollen supplements increase haemolymph protein levels (De Jong et al. 2009) and allowed bees to remove more Varroa-infested brood than bees who were deprived of pollen or who had normal amounts of pollen (Janmaat and Winston 2000).

There is evidence from Ontario studies that supplementing hives is sometimes beneficial. Colonies supplemented with pollen in the spring increased honey yield, brood rearing, and number of workers in the summer (Mattila and Otis 2006b). In a separate study, the same authors investigated whether pollen supplements could increase longevity when honey bees were infected with *Nosema* (Mattila and Otis 2006a). When the authors conducted the experiment using observation hives, they found pollen supplements significantly extended honey bee worker longevity, but this effect was not replicated in their field trials. In their final study examining pollen supplementation, these authors also found supplementing honey bees did not affect their overwintering success in Ontario (Mattila and Otis 2007). However, not all commercial supplements are equally formulated; the quality of syrup and pollen substitute also directly impacts bee health. Bees fed pollen substitutes do not live as long as bees fed high quality pollen diets (Wahl and Ulm 1983). A Canadian study found that protein quantity and quality changes the foraging behaviour of honey bees to collect more pollen in an effort to compensate for low protein (Pernal and Currie 2001). A European study determined diet quality also interacts with pesticides, where bees fed low quality pollen substitutes are more sensitive to various pesticides than bees fed high quality pollen diets (Wahl and Ulm 1983). Pollen supplements that are made from proteins other than soy are also shown to be detrimental. For example, soybean and lupin protein patties were shown to reduce honey bee lifespan when compared to pollen patties (Manning et al. 2007).

Providing hives with high fructose corn syrup (HFCS) is the most affordable and easiest carbohydrate supplement for beekeepers, but there have been some concerns about its health effects on bees. Currently, there is conflicting evidence about the negative health impacts of high fructose corn syrup and sucrose syrup for honey bees, and no evidence exists from Ontario or Canada. Some studies find no negative health effects from using high fructose corn syrup as a carbohydrate substitution, and that colonies grew faster compared to those not receiving supplemental feeding (Johnson et al. 2014). Furthermore, supplemented carbohydrates, in the form of HFCS or sucrose syrup, did not alter the chalkbrood infection rate of honey bees (Yoder et al. 2014). Conversely, Wheeler and Robinson (2014) found differences in expression of hundreds of genes when they compared between workers raised on either sucrose syrup or high fructose corn syrup compared to honey. They also observed between workers fed HFCS and sucrose syrup. These results suggest that these substitutes do not contain all of the ingredients that are found in honey and may not provide a comprehensive and balanced food source for honey bees. Another study found that out of the two possible substitutions, sucrose syrup is a better choice than high fructose corn syrup. Colonies fed on sucrose syrup built more comb and contained more workers (Sammataro et al. 2013). These studies suggest that supplementing hives is beneficial, but mostly when they are being supplemented with high quality diets (i.e., pollen patties made with real and polyfloral pollen as a protein source, and actual honey or sugar water instead of high fructose corn syrup as a carbohydrate source).

Emerging research on honey bee supplementation is examining new avenues such as vitamin and probiotic supplements. One study found that provisioning honey bees with vitamin C led to higher protein contents and higher antioxidant enzyme levels in workers. In addition, overwintering mortality was 33% lower than in bees that did not receive the supplement (Farjan et al. 2012). Probiotics are showing mixed results in honey bee health. A study in Europe found that supplementing bee diets with probiotics led to an increase in *Nosema* spp. infection (Andrearczyk et al. 2014). Other studies report benefits such as

reduced microbe levels in bees fed probiotics (Patruica and Mot 2012), and increased gut membrane development (Szymas et al. 2012). Although there is established evidence that a healthy gut microbiota is essential for honey bee health, there is currently insufficient evidence to show that supplementing hives with probiotics is beneficial.

One study in Canada examined the effects of supplementing laboratory reared *B. impatiens* colonies on reproductive success (Pelletier and McNeil 2003). The authors supplied bees with *ad libitum* sucrose solution and pollen patties and found that both their colony size and colony reproductive success increased compared to colonies that were not supplemented. The number of young queens generated also increased as food supply increased, ensuring future generations of bumble bees for later crop pollination. A subsequent study by the same authors found that supplementing colonies with *ad libitum* sucrose solution and pollen patties led to a reduction in forager activity (Pelletier and McNeil 2004). It is likely these bumble bees foraged less because they did not need bear the risk and energetic cost of foraging when they had sufficient food in the colony stores (Molet et al. 2008).

### Overwintering Practices

In Ontario, management practices are the second leading cause of overwintering mortality in honey bees after *Varroa* mite infestation (Guzman-Novoa et al. 2010). Specifically, having weak colonies, with insufficient numbers of workers entering the winter season, and having limited food reserves to carry bees through the winter contributes to their losses. Beekeepers can overwinter their colonies outdoors or indoors, and one Canadian study found where hives are overwintered can affect honey bees. Williams et al. (2010) found there was no difference in *Nosema* levels between colonies overwintered inside or outdoors, but there were higher losses in late spring in hives that were overwintered outside. Furthermore, starvation and poor queens have been attributed to overwintering losses recently in Ontario (Kozak 2010, 2014b).

Overwintering practices are the main management practices researched for other managed bees. For *O. lignaria*, farmers receive them as pupae and refrigerate them until they would like to time their emergence as adults with orchard blooms. Proper timing ensures synchrony with blooms and maximizes pollination services. Varying the temperature that pupae are stored at, as well as the duration of cold temperature exposure, affects when the bees will eclose and is effective for producing bees to pollinate early spring blooming crops and late blooming crops (Bosch and Kemp 2000, 2003; Kemp and Bosch 2000; Pitts-Singer et al. 2008). Many growers interested in these managed bees are deterred from using them because they do not own climate-controlled facilities. However, a recent Canadian study found that overwintering pupae in a sheltered area outdoors results in high survival, and bees naturally emerged with well-timed synchrony with apple blossoms (Sheffield et al. 2008a). Furthermore, it is easier to overwinter bees that are from the local climate region. Survival rates were higher for progeny of local bees compared to progeny of imported bees from other climate regions (Sheffield et al. 2008b). This study illustrates that *Osmia*, a highly efficient alternative pollinator to honey bees, can be easily managed in Canadian climates. Research in Ontario could investigate whether these low maintenance overwintering strategies are effective here as well.

Like *Osmia*, the emergence of *M. rotundata* can be manipulated based on temperature and duration of pupation (Richards et al. 1987). It is recommended that *M. rotundata* be overwintered in a temperature-controlled facility that allows for control over emergence

timed with the alfalfa bloom, since this species is used to pollinate one crop in Ontario (Richards 1984). Maintaining a temperature controlled overwintering room also reduces the development of pathogens.

### **Treating and Preventing Pests, Pathogens, and Natural Enemies**

Regular monitoring for pests and pathogens, and treating them as necessary, is another management practice important for Ontario, as ineffective management of *Varroa* and *Nosema* have been reported by beekeepers as contributing to overwintering losses (Kozak 2010, 2013b). A European study found that failing to use preventative treatments to control for *Varroa* was the main risk factor for colony mortality in France (Chauzat et al. 2010). Last year OMAFRA reported low levels of *Varroa*, showing that effective hive management is keeping infestations manageable in Ontario. It is also important that beekeepers treat on time against *Varroa* (early spring and or early fall) and rotate their registered synthetic miticides with formic acid or thymol to reduce the likelihood of mite resistance, which is beginning to become an issue in Ontario (Kozak 2014b) and is further outlined in the Pests and Pathogens section (see page 66). Management practices have also been developed to reduce the exposure to pests, pathogens, and enemies in other managed species. Richards (1984) published a comprehensive guide to managing *M. rotundata* in Canada that outlines ways to decontaminate nest materials using bleach or steam. Managing *M. rotundata* to reduce chalkbrood levels is achieved by releasing pupae as loose cells (instead of in their nest) to prevent adults from contracting chalkbrood spores from infected dead larvae in the same nest, and has been shown to reduce infection levels (Bosch and Kemp 2002). Reducing predation by birds is effectively accomplished by covering nesting boxes with a screen, and from wasps is accomplished by using thick cardboard tubes or reeds (Bosch and Kemp 2002).

### **Other Management Practices**

High genetic diversity in honey bees improves their immunity against pathogens and promotes colony growth (Tarpay 2003; Tarpay et al. 2013). It has been thought that breeding for specific traits (e.g., honey production, docility, hygienic behaviour) reduces genetic diversity, which may in turn may have negative implications for honey bee immunity. In Ontario, Harpur et al. (2014) reported that artificial selection for *Varroa* resistance through hygienic behaviour does not affect innate immunity. Harpur et al. (2012) also found that managed bees actually have higher levels of genetic diversity than their unmanaged progenitors, although the conclusions drawn from this paper have been questioned (De la Rua et al. 2013).

Another honey bee management practice is the effect of applying brood pheromone to beehives. Brood pheromone is naturally released by developing larvae in the colony and serves as a demand signal for workers to collect pollen and nectar to feed larvae. Canadian studies have shown that treating their colonies with synthetic brood pheromone has increased spring worker populations (Moeri et al. 2011), overwintering success, and honey production (Lait et al. 2012).

Research is being conducted to develop good nesting sites for *O. lignaria*. One US study found that *Osmia* are able to successfully nest in a variety of materials, but prefer wood and styrofoam over other materials (Torchio 1982). Keeping original nests every year is advantageous because females prefer to choose holes in the same general area as their previous nesting site (Tepedino and Torchio 1994). Hole size in nesting site influences the size and sex ratio of offspring produced; the recommended diameter is 7 or 8 mm. Pupae



are not affected by rough handling or being shaken (Tepedino and Torchio 1989), allowing them to be transported between orchards before adult emergence. Despite the ease of constructing bee housing, growers need to consider the number of bees they use. Saturating orchards with these bees can lead to pollen and nectar shortages that can limit population growth and increase mortality leading to possible problems for commercial bee breeders (Jahns and Jolliff 1991; Torchio 1985). The number of bees recommended to pollinate one hectare of apples is 625 (Bosch and Kemp 2002).

### **Impacts of Invasive Alien Insects**

Invasive insects have considerable potential to have impacts on wild bees and other pollinators. Ecological impacts of invasive insects include competition for floral resources and nesting sites, transmission of pests and pathogens, and reproductive disruption with interspecific mating.

In Ontario, *O. lignaria* and *A. mellifera* are commonly used species for crop pollination but are non-native. To date, *A. mellifera* is the most widely distributed alien pollinator in the world (Kearns et al. 1998) and its potential impacts on wild pollinators have received considerable attention. In coastal California, Thomson (2004) experimentally introduced honey bees and found that their proximity to hives significantly reduced the foraging rates and reproductive success of wild *Bombus occidentalis* colonies. Others have also found that honey bees commonly deter other bee species from foraging on high quality sources of forage (e.g., Eickwort and Ginsberg 1980; Gross 2001; Rogers et al. 2013a). Rogers et al. (2013a) found that when *B. impatiens* encountered *A. mellifera* they discontinued foraging at that floral resource. Their work, along with others, show that *Bombus* spp. and other solitary-foraging wild bees that encounter *A. mellifera* may be locally displaced from the source of the encounter. The invasive potential of non-native pollinators is increased by the possibility of an inseminated queen founding a new colony, and consequently producing a number of reproductive individuals (Moller 1996). Other invasive alien insects include ants, which may also impact wild bees. For example, the invasive Argentine ants (*Linepithema humile* Mayr) have also been shown to reduce the amount of time wild bees spend foraging on flowers, or to displace them entirely (Altshuler 1999; Lach 2008).

Honey bees and bumble bees are generalist species, and can therefore interact with a significant proportion of wild bee fauna (Goulson 2003a) and may deplete nectar and pollen. In Arizona, Schaffer et al. (1983) found that honey bees reduced the standing nectar crop in *Agave schottii* flowers for wild bees. In Australia, Gross (2001) observed fewer visits by wild bees to *Dillwynia juniperina* flowers when honey bees were also foraging on these shrubs, and depleting the standing crop of nectar. Similarly, Dupont et al. (2004) found that honey bees stayed longer and visited more flowers per inflorescence than wild bees, depleting nectar levels in *Echium wildpretii* flowers. To the best of our knowledge, no studies have looked at resource competition between honey bees or other alien pollinators and wild species. However, most researchers agree that resource depletion has resulted in a significant competition in favour of invasive alien bee species (Goulson 2003b). Conversely, Horskins and Turner (1999) did not find that honey bees depleted resources of a native plant.

## Wild Pollinators

### **Habitat Restoration**

There is well established evidence from Ontario and Canada that restoration practices have positive effects on pollinator communities (Grixti and Packer 2006; MacKay and Kerner, 1979; McLeod 2013; Rutgers-Kelly and Richards 2013; Taylor and Catling 2011). The majority of studies from Ontario that have examined the impacts of restoration on bee communities have focused on examining changes in functional diversity over time. Examining changes in functional guilds allows for a deeper understanding of how pollinator communities respond to management practices, such as restoration. Collectively, studies have shown that functional guilds do not respond similarly to restoration practices (Grixti and Packer 2006; Taylor and Catling 2011). Specifically, ground nesting species tend to move more quickly into newly restored areas compared to cavity nesting species (Rutgers-Kelly and Richards 2013), likely due to the greater availability potential nesting substrates. A study from eastern Canada also showed similar functional guild responses. Sheffield et al. (2013) showed that intensely managed orchards had significantly lower species richness than in old or abandoned fields that were in early stages of succession.

Evidence from the USA also shows a positive impact of restoration on pollinators (Morandin and Kremen 2013a; Thorp 2012; Williams 2011). There are several studies that have demonstrated that traditional restoration seed mixtures of native perennial plant species have a positive impact on the presence of wild bees in habitats (Harmon-Threatt and Hendrix 2015; Herron et al. 2013; Hopwood 2008). To ensure pollination services provided by wild pollinator communities are maintained in agroecosystems, conserving and restoring natural land with floral resources close to cropland is beneficial (Blaauw and Isaacs 2014a, 2014b; Hannon and Sisk 2009; Morandin and Kremen 2013a). Studies have indicated that the overall success of habitat restoration mainly relies on ensuring plant-pollinator mutualisms are established (Cusser and Goodell 2013; LaBar et al. 2014) and phenological diversity is established in seed mix varieties or plantings (Havens and Vitt 2016). However, many studies that have examined the impact of restoration on wild bees have suggested that bee community differences in restored habitats do not arise primarily from differences in the composition of the flowering-plant community; rather other physical characteristics of restored habitats lead to the different pollinator communities (Williams 2011; Winfree 2010). Ensuring the other necessary physical characteristics of restored habitats are present is also likely to help safeguard against further pollinator declines (Roulston and Goodell 2011).

Similarly to results from North America, studies from Europe have also demonstrated that bee communities in restored natural and semi-natural habitat are primarily structured by local-scale factors associated with nesting resources rather than structured by floral resources (Murray et al. 2012; Sarospataki et al. 2009; Sydenham et al. 2014). However, several studies have suggested small-scale restoration projects are better at maintaining higher species diversity compared to larger restored habitats (Beil et al. 2014; Klein et al. 2012; Moron et al. 2014). This is due to the fact that smaller restored habitats can support more specialized and less-mobile species (Beil et al. 2014; Klein et al. 2012; Moron et al. 2014; Nielsen et al. 2012; Steffan-Dewenter et al. 2002) and in turn higher levels of species richness.

## Land Management

There is established evidence from Ontario and Canada showing positive impacts of habitat management such as the use of fire on wild pollinators, specifically bees. In Ontario, there is very little evidence on the impact of agricultural management practices, such as retaining or restoring natural habitat near or between agricultural fields thereby encouraging and supporting pollinators species used for these crops. One study demonstrated varying impacts of fire as a tool for maintaining oak savannah habitat on bee guilds. This study found that ground nesters tend to respond immediately and positively after a burn, whilst cavity nesters and *Bombus* spp. mostly show negative and delayed responses to fire management (Pindar and Packer in review; Taylor and Catling 2011). There is also evidence from Canada suggesting that intermediate levels of management practices can maintain higher diversity for longer when compared to intensely managed or abandoned habitat (Sheffield et al. 2013b). This suggests that bee biodiversity is maintained, or maximised, in natural and semi-natural habitats with an intermediate level of management.

Similarly to Canadian research, studies from the USA and Europe have also reported positive effects of land management such as grazing, logging, agricultural management, tillage and fire on pollinators (Knop et al. 2006; Moretti et al. 2009; Potts et al. 2003; Vulliamy et al. 2006; Williams et al. 2010; Winfree et al. 2009, 2011). Collectively, these studies from the US and Europe have shown that bee communities are at their highest diversity levels following the implementation of management practices (Moretti et al. 2004; Potts et al. 2001; Williams et al. 2010). That is, habitat management practices increase bee biodiversity in ecosystems. Although the literature indicates that bee species tend to respond positively to habitat management, high species diversity is almost always short-lived where by an intermediate time, diversity is significantly less than previously recorded (Potts et al. 2006; Winfree et al. 2009).

There is no established evidence from Ontario demonstrating the impact of agricultural management on wild pollinators. However, there is well established evidence from the USA and Europe showing significant positive impacts on wild pollination communities. Many studies have highlighted the importance of planting native floral resources as an essential agricultural management practice for safeguarding pollination services provided by wild bees in agroecosystems (Bartomeus et al. 2014; Kremen et al. 2004). For example, studies in the US have shown that planting floral resources near high bush blueberry fields significantly increased fruit set and weight of blueberries (Blaauw and Isaacs 2014a, 2014b; Tuell et al. 2009). There is also well established evidence that pollination services from wild bees are positively related to the proportion of natural or semi-natural habitat in the vicinity of crop land (Brosi et al. 2008; Gonthier et al. 2014; Kremen et al. 2004; Morandin and Winston 2006). In addition to native plantings safeguarding pollination services, they also provide pollen and nectar resources when the crop is not in bloom and may also provide nesting habitat (depending on the bee species biology: Le Feon et al. 2010; Tscheulin et al. 2011; Wood et al. 2015).

## Impacts of Invasive Species

Invasive insects have the potential for considerable impacts on wild bees and other pollinators. Ecological impacts of invasive insects include competition for floral resources and nesting sites, transmission of pests and pathogens (see page 67), and reproductive disruption with interspecific mating.

There is established, but incomplete, evidence on competition between invasive alien and wild bees for nest sites. One example is a study by Barthell et al. (1998) who found that two managed bees (*Megachile apicalis* and *M. rotundata*, the latter of which is used commercially in Ontario) and the European earwig (*Forficula curicularia*), occupied more trap-nests than wild bees in California. Stout and Morales (2009) infer potential competition for nest sites based on niche overlap as managed *B. terrestris* queens use nest sites that are similar to wild *Bombus* in a number of regions. This is an area in which further research is needed. Mating between alien and wild subspecies has been reported to occur and has been shown to have genetic consequences. In Europe for example, mating between *A. mellifera ligustica* and *A. m. carnica* with wild *A. m. mellifera* has replaced the subspecies entirely, especially in Germany (De la Rua et al. 2002; 2009; Jensen et al. 2005). Similarly, commercial use of alien *B. terrestris* subspecies in Europe has shown potential to interbreed with subspecies *B. terrestris audax* (Ings et al. 2005). In a laboratory experiment, Kanbe et al. (2008) showed that mating between *B. terrestris* and *B. hypocrita sapporoensis* produced inviable offspring hybrids in Japan. Mating between alien and wild species has shown to have negative effects on the reproductive rate and ability to produce viable offspring (Kanbe et al. 2008).

### Suggestions

Conserving or restoring natural land with native flowering plants adjacent to cropland is highly recommended to attract pollinators and maintain species richness and abundance. In addition to restoring land with native plant species, it is strongly recommended to incorporate into the landscape other physical habitat characteristics, such as cavities created from dead wood, to provide nesting resources for wild bees. We also suggest providing beekeepers with up-to-date best management practices for how and when to perform the following: 1) supplement hives with additional food, 2) monitor and treat pests and pathogens and 3) prepare colonies to increase overwintering survival. More research is needed on the effects that large-scale migratory beekeeping and monocultures might have on honey bee health and behaviour as demands for pollination services increase in Ontario and surrounding provinces. The extent of inter-specific competition between non-native and native species and its impact on foraging behaviour is relatively unknown. In addition, studies on impacts of invasive species should be broadened to the landscape scale and long-term implications need to be better understood. Furthermore, the implications of climate change on the spatial shifts of invasive plant and animals species and their interactions should be better evaluated. Lastly, more research is needed with regards to management practices in other managed pollinators, including ways to reduce *Bombus* escape from greenhouses and the associated pathogen spill over to wild bees, as well as monitoring and treating for pests and pathogens in all managed pollinators.

## AGRICULTURAL RELIANCE ON POLLINATORS

### Executive Summary

Pollinators are essential for agriculture as 76% of the leading global food crops (including many fruits, vegetables and seed crops) are pollinated by animals. In addition, pollination is essential for maintaining wild flower diversity in both managed and agricultural ecosystems. Currently populations of at least 78 Ontario plant species may be in decline because they receive insufficient pollination (Table 9), however evidence for this is currently speculative. Little is known about the pollinators of rare plant species, which is a cause for concern given that pollination is essential for the long-term survival of most flowering plant species.

In Ontario there are 32 economically important crops, representing 6 major types (orchard fruit, berry fruit, field fruit and vegetables, forage and oilseeds, greenhouse crops, and other crops) that require insect pollination. There is considerable evidence demonstrating the importance of flower visits by insects to crop pollination globally, particularly for the 6 major crop types found in Ontario. An emerging theme from this global evidence is that proximity of natural or semi-natural habitat to agricultural lands is frequently linked to increased yield in a range of crops, although such information is not currently available for Ontario. These insect dependent crop types represent approximately 2.67 million hectares of land in Ontario. However, in comparison to the number of studies investigating pollination of crops relevant to the province from the USA and Europe, there is considerably less evidence from Ontario or Canada. In addition, information on pollinator contribution to crop pollination is dated or generally lacking for many Ontario crops (including soybeans).

Most pollination research has focused on investigating the importance of honey bees for agricultural crops, however there is well established evidence of the importance of wild pollinators for increased fruit set in both wild plants and a range of economically important crops around the world. Currently, research on the importance of wild pollinators for crop pollination in Ontario is severely lacking. This is concerning given wild pollinators are linked with increased fruit set in at least 34% (11 of 32) of the insect dependent crops in Ontario. The financial implications of this knowledge gap are unclear because it is unknown how much the estimated value (\$895 million/year) of pollination services to crops in the province are provided by wild pollinators.

### Introduction

Pollination services provided by bee communities are one of the most crucial ecosystem services (Kremen et al. 2007). Bee pollination by bees in North American agroecosystems is worth billions of dollars every year (Kevan and Phillips 2001; Kremen et al. 2002a) with both direct and indirect influences on the global economy (Committee on the Status of Pollinators in North America 2007; Gallai et al. 2009; Lautenbach et al. 2012). Eighty percent of the world's agricultural crops are pollinated by *A. mellifera* (Carreck and Williams 1998); however, wild pollinators are also important contributors if sufficient natural habitat areas are available to support them (Breeze et al. 2011). Along with its crucial economic role, pollination also plays an important ecological role. Pollination helps maintain wild flower diversity in both managed and agricultural ecosystems. Furthermore, non-crop flowers can increase crop yield by providing additional resources for crucial pollinator species (Sheffield et al. 2008b). More generally, pollination helps to sustain all

the other organisms in an ecosystem that depend on resources ultimately obtained from flowering plants.

Pollination is arguably one of the most critical global ecosystem services with approximately 87.5% of the world's flowering plant (angiosperm) species pollinated by animals (Ollerton et al. 2011). While this interaction undoubtedly contributes to global terrestrial biodiversity, our direct dependence on this interaction is enhanced considerably due to our heavy reliance on pollinators for seed or fruit production in many agricultural crops. Widely known estimates suggest that about one-third of our food, including animal products, is derived primarily from bee-pollinated crops (Garibaldi et al. 2014; Klein et al. 2007; Kremen, 2008; McGregor, 1976; Winfree, 2008). In Europe, pollination has been reported to improve the fruit or seed quality or quantity of about 85% of 264 cultivated crops (Williams, 1994). Klein and colleagues (2007) estimated that pollinating insects increase yield or quality of fruit or seed in 39 of 57 major crops worldwide.

### **Pollinators in Agricultural Systems**

#### **Managed Pollinators**

The managed honey bee (*A. mellifera*) is the most commonly used agricultural pollinator in North America and around the world (Delaplane et al. 2000; James and Pitts-Singer 2008; McGregor 1976; vanEngelsdorp et al. 2010). Farmers in Ontario rent more than 30,000 colonies every year for crop pollination services (Kozak 2015a; Figure 12). Demand for honey bee colonies to provide these pollination services continues to rise in Canada due to expansion of agricultural acreage (Kozak 2015a). However, this demand for pollination services is increasing during a time when beekeepers are experiencing significant colony losses, and consequently the cost of renting each hives has risen from \$50-65 in 1995 to as much as \$140 in 2015 (Eccles pers. comm.).

However, not all agricultural crops are pollinated effectively by honey bees. For example, tomatoes require buzz pollination (Dogterom et al. 1998; Morandin et al. 2001a, 2001b), a behaviour honey bees cannot perform but can be delivered effectively by bumble bees. Managed bumble bees have also shown considerable potential in field crops. For example, Stanghellini et al. (1998) found that watermelon (*Citrullus lanatus* Thumb.) flowers visited by *B. impatiens* had lower fruit abortion rates and higher seed set than those visited by honey bees. Alfalfa flowers are better pollinated by the native alfalfa leafcutter bees (*M. rotundata*) than by honey bees (Brunet and Stewart 2010; Cane, 2002). Furthermore, honey bees do not work well in greenhouses or under row covers (Dag and Eisikowitch 1995; Sabara et al. 2003). Fortunately, other managed- and wild bees can be more efficient pollinators for some agricultural systems and wild plants species. For example, the native blue orchard bee (*O. lignaria*) has been developed as a managed pollinator for orchard crops (Gardner and Ascher 2006; Sheffield et al. 2008a, 2008b, 2008c). Blue orchard bees show a strong foraging preference for fruit trees (Bosch et al. 1999, 2000; Torchio 1976, 1981, 1982) and have a short foraging range (Bosch et al. 2001), thus their flower visits are concentrated on fruit trees within the target orchard environment (Bosch et al. 2006).

#### **Wild Pollinators**

Traditionally, crop pollination needs were met entirely by wild pollinators in agricultural landscapes (Kevan et al. 2001). At present, it is currently unknown how many unmanaged species contribute to crop pollination, nor what percentage of crop pollination results from wild species (Kremen 2008). Thousands of bee species visit crop plants worldwide (Free

1993), but few intensive surveys have been conducted to confirm their contribution and the value they add to production. A recent meta-analysis by Garibaldi and colleagues (2013) reported increases in fruit set as a result of increased flower visitation by wild insects in all 41 cropping systems they assessed. They also reported that fruit set increased with flower visitation by honey bees in only 14% of the crops studied (Garibaldi et al. 2013). In a few cases, native bees have been found to be more effective pollinators than honey bees. For example, in North America, 190 wild bee species are associated with lowbush blueberry (Kevan et al. 1990), and in California, 65 wild bee species were observed in summer crops (Kremen et al. 2002a). However, the degree to which other wild pollinator groups (including flies, wasps, butterflies, moths, beetles, hummingbirds and bats) contribute to pollination remains largely unknown, but it is generally considered likely that they also make significant contributions.

### Summary of Evidence

Investigating pollinators of crops is an active area of research worldwide and we found well established evidence of the importance of insects to crop pollination. Overall there is considerably more established evidence investigating the importance of honey bees for pollination of agricultural crops compared to the number of studies found investigating the importance of wild pollinators. There is also well established evidence for the importance of other managed pollinators, such as managed bumble bees, blue orchard bee (BOB) and the alfalfa leafcutter bee (ALCB), for crop pollination in Canada, the USA and Europe. Furthermore, we found considerably less evidence investigating the importance of pollinators to crop production from Ontario and Canada compared to the USA and Europe. This is concerning given that agricultural production in Ontario accounts for almost 25% of Canada's gross revenues from agriculture yet evidence on pollinators is significantly lacking.

There is a substantial disconnect between the number of pollination studies that have been conducted on key agricultural crops compared to the economic value of those crops. For example, we found a substantial number of studies investigating pollinators of orchard and berry crops compared to other crop types found in Ontario, yet the economic value of these crops is significantly lower.

There have been repeated attempts to quantify the economic value of pollination services to agricultural systems in North America and worldwide. Overall, we found substantial variation in these estimates of the value of pollination services at regional and global scales, but we found no study that attempted to quantify the value of pollination services at a local scale. There is evidence that our capacity to quantify the risk of lost agricultural value due to wild pollinator declines is severely compromised by knowledge gaps. To address these issues we need further investigation into: (1) the degree to which yield and quality of many crops are truly dependent on insect pollination (this is currently relatively unknown); (2) the proportion of pollination contributed by wild pollinators (these values are assumed in reported calculations of economic values of pollination services); and (3) how pollinator losses may directly impact yield for a wide range of crops.

Current information on the pollinator contribution to crop pollination is relatively dated or lacking for many important crops grown in Ontario. Overall, we found limited evidence from studies conducted in Ontario examining crop pollination. We found no published studies from Ontario investigating pollinators or crop pollination for 61% (11 of 18) of Ontario's crops that are dependent on insect pollinators. This is concerning when crops

reliant on specific pollinators are expected to be vulnerable to pollinator declines. However in some specific circumstances, e.g. greenhouse tomato production using commercial bumble bee colonies, such issues can be ameliorated due to their production in heavily managed pollination systems. Investigating the importance of wild pollinators to crop pollination is an active area of research worldwide. We found well established evidence that the combined presence of managed and wild pollinators contributed to increased fruit set in 35% of insect dependent crops in Ontario. We found no evidence from studies conducted in Ontario directly demonstrating the importance of wild pollinators to crop pollination.

### Agricultural and Crop Pollination in Ontario

Currently there are over 57,000 farms in Ontario that require the services of insect pollinators to grow food and fuel crops. Furthermore, Ontario generates almost one quarter of Canada's gross revenues from agriculture (Statistics Canada 2014a), and is home to approximately 25% of Canada's farmers (Figure 13) and 8% of Canadian farmland (Figure 13; Statistics Canada 2012b). Over the last century there have been dramatic shifts in farming and agricultural practices in Ontario. For example, the area of land being farmed in Ontario has decreased 42% since 1921, and the average farm size has nearly doubled from 144 to 233 acres in the same period (Statistics Canada 2012b). In addition to the average farm size doubling, historically, there were nearly four times as many farmers in 1921 as today (1921 vs. 2006). Currently the vast majority of southern Ontario is considered dependable agricultural land with pockets of settlement areas scattered throughout (Figure 13).

In Ontario, 34 key agricultural crops are dependent to some extent on the pollination services provided by managed and wild pollinators, including orchards, berries, field fruit and vegetables, greenhouse crops, oil seed and forage crops (Table 7). Below we present a table (Table 7) outlining, which managed pollinator species and wild pollinator taxa have been, observed visiting flowers of each crop, and the evidence that these visits translated into effective pollination services.

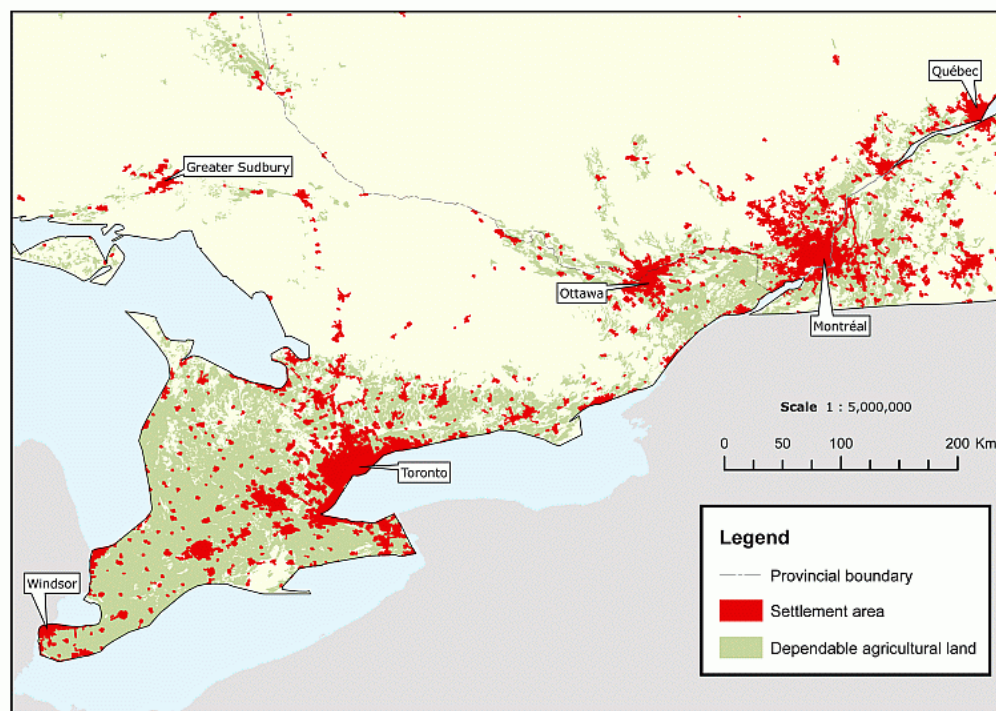
### **Summary of Evidence**

Information on the pollinator contribution to crop pollination is either relatively dated or lacking for many important crops grown in Ontario. Overall, we found limited evidence from studies conducted in Ontario examining crop pollination. We found no published studies from Ontario investigating pollinators or crop pollination for 61% (11 of 18) of Ontario's crops that are dependent on insect pollinators. This is concerning when crops reliant on specific pollinators are expected to be vulnerable to pollinator declines. However in some specific circumstances, e.g. greenhouse tomato production using commercial bumble bee colonies, such issues can be ameliorated due to their production in heavily managed pollination systems. Investigating the importance of wild pollinators for crop pollination is an active area of research worldwide. However, we found no evidence from studies conducted in Ontario directly demonstrating the importance of wild pollinators to crop pollination.

Overall, there is significantly more established evidence examining crop pollinators of the major crop types found in Ontario from studies performed in either the USA or Europe compared to in Canada. Specifically, we found well established evidence from Europe demonstrating the importance of both managed and wild pollinators in pollinating mass flowering crops, such as canola (oilseed rape). We could find no published studies from



Canada investigating soybean crop pollination, which is surprising given the significant economic value of this crop and the fact that yield of legume crops are often highly pollinator dependent.



**Figure 13.** Settlements and dependable agricultural land in southern Ontario and Quebec, 2006.

We also found very few studies assessing the contribution of pollinators to the production of major field crops such as peas and beans, a source of concern given these are leading commodity crops in Ontario (Figure 14). Furthermore, we also found limited evidence on the pollinator contribution to sour and sweet cherry and peach orchard crop production. These crops are considered to be Ontario's leading orchard crops, yet studies on pollinator contribution are severely lacking. Although apple pollination has not been well studied in Ontario, there is well established evidence to support their pollination requirements in Canada, the USA and Europe. Collectively, studies from the USA and Europe have shown that both managed and wild pollinators are significant contributors to apple pollination.

We found no studies from Ontario examining the pollination of either raspberry or cranberry. Established evidence from the USA reports that honey bees are widely used to pollinate cranberries, however, wild pollinators are also important pollinators for this crop. We also found limited evidence from Ontario for the importance of both managed and wild pollinators for blueberry pollination. However, there is well established evidence from the USA showing the importance of native and managed bee pollination in blueberry crops, but little information on the effect that agricultural scale plays in blueberry crop productivity.

We found well established evidence from Canada, including Ontario, supporting the efficacy of commercial bumble bees (*B. impatiens*) for tomato pollination in commercial greenhouses. However, not all bumble bee species are such effective pollinators of greenhouse tomatoes. There were very few studies investigating greenhouse pepper pollination in comparison to the number of studies investigating tomato pollination.

**Table 7.** List of the 34 key agricultural crops found in Ontario and associated pollinators. An X represents evidence that a species or guild has been seen visiting crop flowers. Crops and crop types listed represent the key economical crops found in Ontario. Asterisks indicate no evidence of species or guild visiting crop flowers was found.

	Combined presence increases productivity	<i>Apis mellifera</i>	<i>Bombus</i> spp.	ALCB	BOB	<i>Bombus</i> spp.	Solitary ground nesters	Social ground nesters	Cavity nesters	References
		Managed pollinators				Wild Pollinators				
<b>Field fruits and vegetables</b>										
Cucumber ( <i>Cucumis sativus</i> (Field and pickling))		X	X			X			X	Benachour et al. (2011); Gajc-Wolska et al. (2011)
Melon ( <i>Cucumis melo</i> )		X	X							Iselin et al. (1974); Rader et al. (2013)
Watermelon ( <i>Citrullus lanatus</i> )	X	X	X			X	X	X	X	Rader et al. (2013); Henne et al. (2012)
Squash; Pumpkins; Zucchini ( <i>Cucurbita</i> spp.)	X	X	X			X	X			Artz et al. (2011); Julier and Roulston (2007, 2009)
Peas ( <i>Pisum sativum</i> )			X							Ibarra-Perez et al. (1999)
Green Bean ( <i>Phaseolus</i> spp.)		X	X							Kendall and Smith (1976); Leguen et al. (1993)
Broad Bean ( <i>Vicia faba</i> )		X	X							Kendall and Smith (1976); Leguen et al. (1993)
Field Tomato ( <i>Lycopersicon esculentum</i> )		X				X			X	Greenleaf et al. (2006a); Parker et al. (1990)
Pepper ( <i>Capsicum annuum</i> )		X								Dag and Kammer (2001); Shipp et al. (1994)
<b>Orchard Fruit</b>										
Apple ( <i>Malus domestica</i> )		X	X		X	X	X	X	X	Adamson et al. (2012); Gardner and Ascher (2006); Rosa Garcia et al. (2014); Scott (1988); Scott-Dupree et al. (1987); Sheffield et al. (2012)
Pear ( <i>Pyrus communis</i> )		X	X			X	X	X	X	Calzoni and Speranza (1996); Mayer et al. (1994); Mayer and Lunden (1997)
Plum ( <i>Prunus</i> spp.)	X		X							Calzoni and Speranza (1996)
Sweet Cherry ( <i>Prunus avium</i> )	X	X	X			X	X	X	X	Holzschuh et al. (2012)
Sour Cherry ( <i>Prunus cerasus</i> )	X		X		X	X				Hansted et al. (2015)
Apricot ( <i>Prunus armeniaca</i> )		X				X	X	X	X	
Peach ( <i>Prunus persica</i> )		X								Nyeki et al. (2002); Olivero (1994); Priore and Sannino (1981)
<b>Berry Fruit</b>										
Currant (spp.)		X			X					Fliszkiewicz et al. (2011); Paimetova et al. (2000)
Raspberry or Blackberry or Rubus		X	X			X	X	X	X	Lye et al. (2011)
Strawberry ( <i>Fragaria ananassa</i> )	X	X	X			X		X	X	Albano et al. (2009); Blazyte-Cereskiene et al. (2012); Chiasson et al. (1997)

## Status and Trends of Pollinator Health in Ontario

Highbush blueberry ( <i>Vaccinium corymbosum</i> )	X	X	X	X	X	X	X	X	X	Benjamin and Winfree (2014); Hall et al. (1979); Isaacs and Kirk (2010); Ratti et al. (2008); Rogers et al. (2013b, 2014); Stubbs and Drummond (2001); Tuell et al. (2009)
Cranberry ( <i>Vaccinium macrocarpon</i> )	X	X	X			X	X	X	X	Broussard et al. (2011); Evans et al. (2006); MacKenzie and Winston (1984); MacKenzie and Averill (1995) MacKenzie and Javorek (1997)
<b>Forage and cover crops</b>										
Alfalfa ( <i>Medicago sativa</i> )		X		X		X	X	X	X	Brookes et al. (1994); Cane (2008)
Clover ( <i>Trifolium spp.</i> )	X	X	X	X		X				Dupont et al. (2011); Plowright and Harlting (1981); (Richards, 2003)
Crown vetch ( <i>Coronilla varia</i> )		X		X						Altikrit et al. (1974); Karron (1987); Richards (1997)
Birdsfoot-Trefoil ( <i>Lotus corniculatus</i> )		X								Degradandi and Collison (1980); Murrell et al. (1982)
Lupine ( <i>Lupinus spp.</i> )		X								Forbes et al. (1971)
<b>Oilseeds</b>										
Canola ( <i>Brassica spp.</i> )	X	X	X			X	X	X	X	Bommarco et al. (2012); Morandin and Winston (2005, 2006) Morandin et al. (2007); Stanley et al. (2013a, 2013b)
Sunflower ( <i>Helianthus annuus</i> )		X	X			X	X	X	X	Calmasur and Ozbek (1999); Chandler and Heilman (1982); Greenleaf et al. (2006b); Kim et al. (2006); Parker (1981)
Soybean ( <i>Glycine max</i> )		X				X	X	X		Koelling et al. (1981); Rust et al. (1980); Gill and O'Neal (2015)
Peanut ( <i>Arachis hypogaea</i> )		X								Banks et al. (1985); Girardeau et al. (1975)
<b>Greenhouse crops</b>										
Tomato ( <i>Lycopersicon esculentum</i> )	X		X							Dogterom et al. (1998); Kevan et al. (1991); Morandin et al. (2001b); Whittington and Winston (2004)
Pepper ( <i>Capsicum annuum</i> )			X							Shipp et al. (1994)
<b>Other crops</b>										
American Ginseng ( <i>Panax quinquefolius</i> )**										
Buckwheat ( <i>Fagopyrum esculentum</i> )	X	X				X	X	X	X	

### Field Crops

In relation to the rest of Canada, Ontario is also strong in field fruit and vegetable production (Figure 14; Statistics Canada 2012a). Peas are the leading vegetable crop grown in Ontario, grown in some 14,806 hectares and representing 68% of Canada's crop. Some pollinators will collect pea pollen, and there is evidence to suggest resultant yield increases may occur as a result (Ibarra-Perez et al. 1999). However, peas are generally considered parthenocarpic, meaning they would not need insect pollination. There is some established evidence to support the pollination needs of green beans globally, which are also grown extensively in Ontario at 9,320 hectares. Green beans (*Phaseolus* spp.) include the common green bean, snap bean, pole bean, kidney bean, haricot varieties, lima bean, scarlet and runner beans. While some cultivars are capable of self-pollination (e.g. *P. lunatus*), other varieties (e.g. *P. coccineus* and *P. vulgaris*) exhibit improved yield with insect pollination (Free 1966b; Ibarra-Perez et al. 1999). Ibarra-Perez and colleagues (1999) found that bumble bees were most successful at tripping *P. vulgaris* flowers, a feature linked with improved seed set. McGregor (1976) also supported this view by

reporting that bumble bees visited bean flowers more frequently than honey bees, but that both were frequent visitors.

Field tomatoes are also grown widely in Ontario (10,606 hectares). While there is well established evidence to support the use of bumble bees for greenhouse tomato pollination in Ontario (Kevan et al. 1991) and globally (Banda and Paxton 1991; Dogterom et al. 1998; Kevan et al. 1991; Mel'Nichenko and Nikiforova 1979; Morandin et al. 2001a, 2001b; Palma et al. 2008; Sabara and Winston 2003; Torres-Ruiz and Jones 2012; Whittington and Winston 2004), the practice is less well established for field tomatoes (Greenleaf et al. 2006a). Tomato pollinators must be able to buzz pollinate (sonicate) the flowers, making bumble bees the most common choice. Field tomatoes (grown outside greenhouses) are usually considered to be sufficiently vibrated by wind currents, which cause the pollen to fall onto the stigma leading to maximum seed and fruit set (Lesley and Lesley 1939). However, under calm weather conditions pollination would conceivably be limited. Thus, visitation by pollinators is beneficial as the size and shape of the fruit is dependent on the quantity and distribution of pollen on the stigma (Marr and Hillyer 1968). The effectiveness of wild bees in tomato pollination does not appear to have been studied in Ontario. One study from northern California found that wild bees substantially increased the production of field tomatoes depending on their distance from natural habitat (Greenleaf et al. 2006a). Consequently, when managing for the ecosystem services of wild pollinators, the natural histories and dependency on natural habitats of individual bee species needs to be considered.

Field peppers are not commonly grown in Ontario, and represent a small proportion of the national production. We found no evidence that flower visitors have been seen in Ontario and limited evidence globally. They are generally considered self-pollinating, although evidence of cross-pollination exists (Free 1993; Raw 2000; Tanksley 1984). Several types of bees visit pepper flowers, including both honey bees (Delaplane et al. 2000; Kubišová and Háslbachová 1990) and wild bees (Raw 2000).

Cucumbers, zucchini (corguette), melons, watermelon, squash, and pumpkins all belong to the family curcubitaceae. Pumpkin, squash, zucchini and cucumbers are the most commonly grown curcubits in Ontario, with planted areas ranging from 3,069 to 3,790 hectares per crop. It is generally considered that members of the Curcubit family are pollinated almost exclusively by insects as the flowers of these plants possess certain adaptive morphological characters suited for this type of pollination (Fronk and Slater 1956). Pumpkin is the only cucurbit crop for which pollination has been studied in Ontario. Willis et al. (1995) measured the daily and seasonal patterns of foraging by the squash bee (*Peponapis pruinosa*). They found that the number of bees visiting flowers changed predictably over the course of the day in response to nectar and pollen availability (Willis et al. 1995). Males and females foraged at different times of day, with females dominating visitation earlier, and males later on (Willis et al. 1995).

We found several studies from the USA investigating pollination of pumpkin by both managed and wild species (Artz et al. 2011; Julier et al. 2009; Petersen et al. 2014; Shuler et al. 2005; Wien and Riggs 1979). For example, Artz and colleagues (2011) reported that honey bees were more frequent flower visitors than either *B. impatiens* or *P. pruinosa* in New York pumpkin fields stocked with honey bee hives (Artz et al. 2011). This study also found there were significantly fewer *P. pruinosa* visits in honey bee stocked fields compared to unsupplemented fields. *Peponapis pruinosa* is a native solitary ground nesting bee that feeds exclusively on the pollen of cucurbit species, but visits the flowers a variety

of other plants for nectar (Hurd et al. 1971). A study comparing the pollination efficiency of squash bees and honey bees on summer squash found negligible differences when all parameters were considered (Tepedino 1981). Taken together the evidence suggests that floral and nesting resources are adequate to maintain strong squash bee populations that will provide adequate crop pollination services for pumpkin or squash, making the use of managed honey bee colonies redundant (Artz et al. 2011; Tepedino 1981; Walters and Taylor 2004).

No published studies investigating watermelon pollination were found from Canada, including Ontario, however, there is well established evidence investigating pollination of these crops in the US and Europe (Dittmar et al. 2010; Kremen et al. 2002b; Stanghellini et al. 1998, Walters 2005; Walters and Schultheis 2009; Winfree et al. 2007a). This dearth of published studies from Ontario is concerning as 25% of Canadian watermelon and melon crops are grown in the province (Figure 14), and watermelons have been shown to require insect visits to increase fruit set and yields (Walters 2005; Walters et al. 2002). Several studies in the US have shown that pollinator visits are required to achieve maximum watermelon fruit set and yields. For example, Walters (2005) found that between 16 and 24 honey bee visits are required to achieve maximum triploid watermelon fruit set and yields in Illinois. These results agree with other published studies indicating that watermelon, particularly triploid varieties, require multiple visits from bees after visiting staminate (male) flowers for adequate fruit set (Dittmar et al. 2010; Stanghellini et al. 2000; Vaissière et al. 1996). We also found several studies demonstrating that wild bee species could provide full pollination services on farms located near natural or semi-natural habitat (Henne et al. 2012; Kremen et al. 2002a; Rader et al. 2013). As a result of extensive field surveys two studies have reported a range of bee species visiting watermelon flowers representing several functional guilds: e.g. solitary ground nesters, social ground nesters and *Bombus spp.* (Henne et al. 2012; Kremen et al. 2002a). These results suggest that wild bees can provide adequate pollination services, without the addition of managed honey bees, for a crop with heavy pollination requirements such as watermelon.

Overall, most research on cucumber pollination has been conducted in the USA (Andrews et al. 2007; Kauffeld et al. 1975, Kauffeld and Williams 1972; Lowenstein et al. 2012; Smith et al. 2013; Stanghellini et al. 2002; Steinhauer, 1970; Stephen 1969). We found no studies investigating cucumber pollination in Ontario, however, we did find several studies from Canada. Gingras and colleagues (1999) demonstrated that both the rate of pollination and maximum cucumber circumference were associated with cumulative duration, but not total number, of flower visits by honey bees (Gingras et al. 1999). Overall, this study showed that honey bees can be important for cucumber pollination and influence both the quality and quantity of cucumbers produced (Gingras et al. 1999); and these results agree with other published studies from the US on the role of honey bees in this crop (Barber et al. 2011; Stephen 1969). We also found studies from the US that investigated cucumber pollination by wild bees (Lowenstein et al. 2012; Smith et al. 2013). For example, Smith and colleagues (2013) investigated the effects of natural and semi-natural land cover on wild bee visitation to cucumber and wild bee species richness on organic farms. This study reported that the frequency of wild bee visitation to cucumber flowers was positively correlated with the proportion of natural and semi-natural land in the surrounding landscape, particularly within 250 m of the cucumber patch. These results are consistent with other published studies that have also reported that flower visitation rates from wild bees are increased by the presence of natural and semi-natural areas in the agricultural

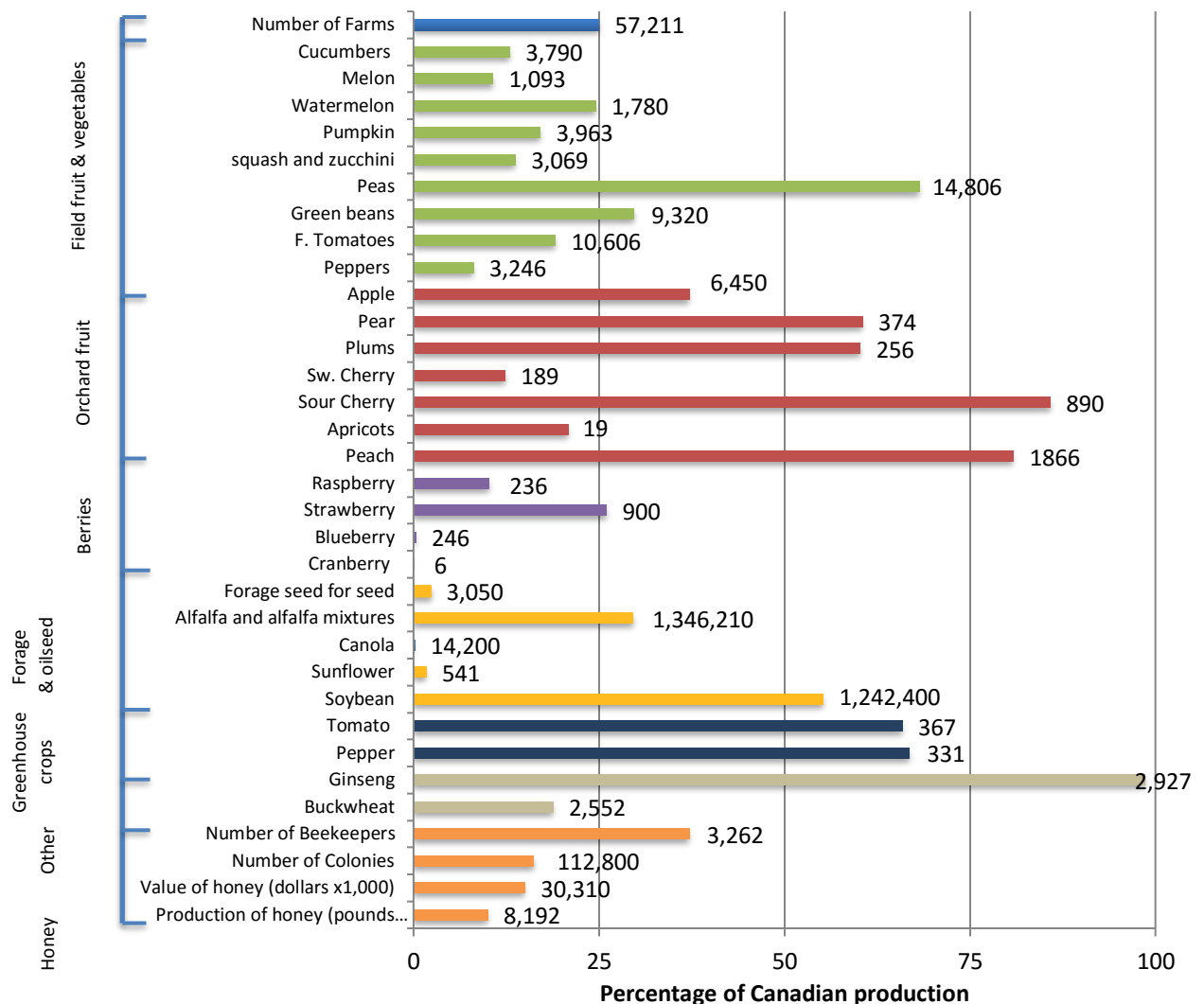
landscape, and these benefits are strongest in the presence of natural areas within 250 m of the crop field (Carre et al. 2009; Kremen et al. 2004; Steffan-Dewenter et al. 1999, 2002).

### Orchard Fruit Crops

The most widely grown tree fruit in Ontario are apples, covering 6,450 hectares (Figure 14). At present, commercial apple orchards typically supplement wild pollinators with managed bees during the bloom period (Allen-Wardell et al. 1998; Free 1966a, 1993). Wild bees, including several species from the genera *Andrena*, *Bombus*, *Halictus*, *Lasioglossum*, *Osmia* and *Colletes*, are known to collect pollen from apple flowers (Atwood 1933; Boyle and Philogene 1983; Gardner and Ascher 2006). Some wild bees, particularly *Andrena* species, have been found to carry greater numbers of pollen grains (Kendall 1973; Kendall and Solomon 1973) and forage in cooler conditions than honey bees (Boyle and Philogene 1983). Although honey bees are not the most efficient pollinators of apples (Parker et al. 1987), adequate pollination can be achieved when they are abundant (Free 1993). When both managed and wild bees are present, the likelihood of successful pollination is higher under the broadest range of environmental conditions (Watson et al. 2011).

Most orchard fruit, particularly peaches and sour cherries are important agricultural crops for Ontario, representing over 75% of the national production (Figure 14: Statistics Canada 2012a). Honey bees (Landridge and Jenkins, 1970; Mayer et al. 1989; Szklanowska and Dabska 1991; Williams et al. 1985) and, to a lesser extent, blue orchard bees (Bosch et al. 2001, 2006) are considered to be the primary insect pollinators of tree fruit crops, although wild bees are also efficient pollinators (Martins et al. 2015; Scott-Dupree et al. 1987; Sheffield et al. 2008b; Watson et al. 2011). Tepedino and colleagues (2007) studied flower visitation by managed and wild pollinators in fruit orchards in central Utah. They found that 33 species of wild bees visited the orchard flowers of apple, pear, apricot and sweet cherry but, except for pear, most were uncommon compared to honey bees.

We found no studies from Canada, including Ontario, investigating pollination of sour cherry, however, there is limited evidence of pollinator contribution from Europe. Hansted and colleagues (2012) investigated the effect of bee pollination on the fruit set of a self-fertile sour cherry (*Prunus cerasus*) cultivar. Using an experimental design, this study showed significantly higher fruit set on open pollinated branches compared to caged (pollinator excluded) branches. Flower visitors on open branches were honey bees, *Bombus* spp. and solitary bees. More recently, Hansted and colleagues (2015) demonstrated that when floral development and seasonal conditions are suitable, there is potential for introduced *Osmia rufa* (aka *Osmia bicornis*) and *Bombus terrestris* to pollinate sour cherry. Specifically this study showed that even though honey bees are conventionally used to increase fruit set, if weather conditions are favorable, alternative managed bee species can increase fruit set (Hansted et al. 2015). These results support the view that when both managed and wild bee populations are present there is an increase in the probability of successful and sufficient pollination services.



**Figure 14.** Ontario farm productivity expressed as a percentage of Canadian national farm output. Data shown are from 2011, the most recent year for which data are available. Values to the right of each percentage bar represent the total farm area (hectares) grown in Ontario by crop type (Statistics Canada 2012a).

### Berry Crops

Berries are grown at small scale (average size is 13 acres) in Ontario compared to farms growing other crops (Figure 14: Statistics Canada 2012a). We found limited evidence examining pollination of blueberry crops from a single study in Ontario reporting that the value of honey bee pollination in lowbush blueberry fields was highly dependent on the presence of wild pollinators, such as *Bombus* spp. (Mohr and Kevan 1997). A study of highbush blueberry and cranberry pollination in British Columbia assessed the abundance and diversity of both managed and wild bees, and found that bumble bees were well distributed within both crops (Ratti et al. 2008). Other wild bee species were well distributed in blueberry fields but generally remained at edges of cranberry fields.

There is well established evidence from the USA showing the importance of native bee pollination in blueberry crops (Benjamin & Winfree 2014; Davis et al. 2003; Isaacs and Kirk 2010; Rogers et al. 2014; Stubbs et al. 1997; Tuell et al. 2009), but little information

on the effect that agricultural scale plays in productivity. Understanding variation in pollination contributions across a landscape gradient is essential. Isaacs and Kirk (2010) compared bee communities in small, isolated blueberry fields with those in large blueberry fields (stocked with managed honey bee hives). Results showed that wild bees were the primary pollinators of small blueberry fields, but were present at low abundance in larger fields (Isaacs and Kirk 2010). Other studies have also reported that wild bees were important for blueberry pollination (Benjamin et al. 2014; Tuell et al. 2009), and showed that wild bees were captured more often at field perimeters than further into the crop. These results demonstrate the importance of natural or semi-natural land surrounding farms for nesting and alternative foraging resources necessary for wild bees. Another study found evidence that both the honey bee abundance, and wild bee species richness were both equally important in blueberry pollination (Rogers et al. 2014). Overall, evidence from the USA adds to a growing body of literature demonstrating that diverse pollinator communities provide more stable and productive ecosystem services for crop pollination (Benjamin & Winfree, 2014; Mandelik et al. 2012; Winfree et al. 2007b).

Ontario's 900 hectares of strawberries accounts for just over 25% of Canada's total strawberry production (Figure 14: Statistics Canada 2012a). In general, strawberry varieties are mostly self-compatible – removing the need for pollination (Klatt et al. 2014). However, published evidence from Canada suggests that both honey bees and wild bees play complementary roles in strawberry pollination and that yield is increased with insect visitation (Chagnon et al. 1993). Furthermore, studies from Europe have demonstrated that wild bees, primarily small solitary bees, are the main visitors of strawberry cultivars (Albano et al. 2009; Blazyte-Cereskiene et al. 2012). Bartomeus and colleagues (2014) reported that insect pollination of strawberry fields enhanced average crop yields dramatically. These results are consistent with other studies that have demonstrated that pollination from wild bees improved fruit quality, quantity and market value (bee-pollinated fruits were heavier and had fewer malformations) compared with wind and self-pollinating strawberry cultivars (Andersson et al. 2012; Klatt et al. 2014).

We found no studies from Ontario examining pollination of raspberry or cranberry crops. This is not surprising given Ontario growers account for less than 10% of Canada's total production of raspberry and cranberry respectively (Figure 14: Statistics Canada 2012a). Overall, studies have shown that honey bees are primarily used to pollinate cranberries (Chagnon et al. 1991; Evans and Spivak 2006; Mackenzie and Winston 1984; Shanks 1969), however, several studies have also reported that wild pollinators are important for cranberry pollination. Small, cultivated cranberry bogs tend to have greater species richness and abundance of wild bees compared to large, cultivated bogs, and consequently also have increased yields (Broussard et al. 2011; Mackenzie and Averill 1995). The effect of crop size on pollinator species in cranberry bogs is consistent with other studies that have reported that increased proximity to natural and semi-natural areas tends to increase pollinator species richness and in turn, crop yields (Ricketts et al. 2008; Schuepp et al. 2014; Steffan-Dewenter et al. 1999).

### **Oilseed Crops**

Ontario's largest and leading agricultural crops reliant on insect pollination are alfalfa, alfalfa mixtures and soybeans, encompassing an area of 1,346,210 ha and 1,242,400 ha respectively (Figure 14). Twenty-nine percent of the national alfalfa and alfalfa mixes are grown in Ontario, compared to over 55% of Canadian soybeans. Surprisingly though, there is limited research on the pollination services provided by insects to these crops in Ontario.



In fact, we found no published studies from Canada investigating soybean crop pollination, yet the economic value of this crop is significant. There is limited evidence from the USA demonstrating the potential value of wild and managed pollinators in soybean pollination (de Milfont et al. 2013; Gill and O'Neal 2015; Rust et al. 1980; Severson et al. 1987; Tew and Caron 1988). Two recent studies reported that corn and soybean fields in central Iowa supported comparatively diverse pollinator communities containing at least 60 species, morphospecies, or higher-level taxa using pan trap sampling, and that the majority of shared species found in both crop types were ground nesting wild bees (Wheelock and O'Neal 2016; Wheelock et al. 2016). de Milfont and colleagues (2013) experimentally demonstrated showed that allowing flower visitation by wild pollinators leads to higher soybean yields. Specifically, this study showed a yield increase of 6.34% in areas where wild pollinators were present. The introduction of honey bee colonies to soybean fields further raised the yield by 18.09%. These results agree with other published studies that have shown the combined importance of both managed and wild pollinators in increasing seed set and crop yields (Garibaldi et al. 2013; Severson et al. 1987).

Many studies have demonstrated the importance of insect pollination for various cultivars of oilseed crops, such as canola, soybeans and sunflowers (Carre et al. 2009; Kovács-Hostyánszki et al. 2013; Morandin et al. 2005). Though canola is not a widely cultivated crop in Ontario compared to other parts of Canada, we found well established evidence supporting dependence on pollinators for seed production (Banaszak et al. 2014; Bartomeus et al. 2014; Morandin et al. 2005, 2006; Stanley et al. 2013a, 2013b). Canola is grown, (alongside soybean) at considerable agricultural scales, averaging 141 (and 131 for soybean) acres per farm respectively, in Ontario (Figure 14: Statistics Canada 2012b). Extensive monoculture crops such as these are exceedingly difficult for pollinators to access and pollinate the interior of the crop due to large field sizes (Bailey et al. 2014). Several studies have reported that pollinator abundance and diversity is highest at field edges, closely associated with higher yields along crops edges (Bartomeus et al. 2014; Morandin et al. 2005; Westphal et al. 2003). For example in Western Canada, Morandin and colleagues (2005) reported bee abundance was greatest in canola fields that had larger areas of uncultivated land within 750 m of field edges with enhanced seed set in fields with higher bee abundance.

There is well established evidence from Europe demonstrating the importance of both managed and wild pollinators in pollinating mass flowering crops, such as winter canola (Basualdo et al. 1998; Bommarco et al. 2012; Garratt et al. 2014; Holzschuh et al. 2013; Stanley and Stout, 2014; Westphal et al. 2003; Westrich 1997). Several studies have reported that canola flowers are visited by a wide variety of insect species, including the honey bee, bumble bees, solitary bees, and hoverflies (Basualdo et al. 1998; Calder 1986; Le Feon et al. 2013); however, honey bees and bumble bees appear to be better pollinators for this crop (Stanley and Stout, 2014; Westphal et al. 2003). Although, studies have shown managed pollinators to be superior at pollinating mass flowering crops, studies have also shown the importance of wild pollinators (Holzschuh et al. 2013; Le Feon et al. 2013; Westphal et al. 2003). For example, Le Feon and colleagues (2013) investigated the impact of natural and semi-natural habitats, canola and other crops on bee community composition by estimating the spatial heterogeneity of the crop field mosaic. This study reported that solitary bee abundance and species richness were both higher in field margins of canola crops than in margins of other fields (Le Feon et al. 2013). In addition, they also successfully showed that early spring-flying species widely use this mass flowering crop. These results are consistent with other work demonstrating that bumble bee abundance was

positively correlated to the availability of highly rewarding mass flowering crops, e.g. canola, in the landscape (Westphal et al. 2003). These findings were supported by Holzschuh and colleagues (2013) when they assessed the interactions between mass-flowering canola fields and semi-natural grasslands at different spatial scales across 67 study sites. This study demonstrated that mass-flowering agricultural habitats, even when they are intensively managed, strongly enhance the abundance of wild bee species nesting in nearby semi-natural habitats (Holzschuh et al. 2013). We also found one study showing that mass flowering crops negatively affected pollinator abundance in both mass flowering crops and adjacent semi-natural habitats, at the landscape-level across six European regions (Holzschuh et al. 2016). Specifically, the abundance of bumble bees, solitary bees, managed honey bees and hoverflies were negatively related to the cover of mass flowering crops in the landscape. Furthermore, in semi-natural habitats, the abundance of bumble bees declined with increasing cover of mass flowering crops while the abundance of honey bees increased (Holzschuh et al. 2016).

We found no published evidence investigating pollinator contribution to sunflower production in Canada, but evidence exists from the USA (Chandler and Heilman 1982; Greenleaf et al. 2006b; Kim et al. 2006; Parker 1981). Several studies found that pollinator contribution from wild bees was higher when natural habitat was in close proximity to crop fields (Greenleaf et al. 2006b; Kim et al. 2006). Interactions between wild and honey bees increased the pollination efficiency of honey bees on sunflower, effectively doubling honey bee pollination services in the average field (Greenleaf et al. 2006b). These findings are consistent with results on the pollinator contribution to canola fields, which showed yields are generally higher along field edges compared to crop interiors (Morandin et al. 2005).

### Greenhouse Crops

Greenhouse tomatoes and peppers grown in Ontario account for 75% of Canada's greenhouse crops (Figure 14: Statistics Canada 2012b). Although tomatoes are largely self-fertile plants, the flowers require agitation of the anther cone to release pollen (Kevan et al. 1991). Historically, tomato plants in greenhouses were pollinated by people using electric pollinators to release pollen (Dogterom et al. 1998), however in recent decades commercial greenhouses have been using managed bumble bees as their primary means of tomato pollination (Kevan et al. 1991; Morandin et al. 2001a; Parker and Tepedino 1990; Velthuis and van Doorn 2006; Whittington and Winston 2004;). There have been many studies investigating tomato pollination in commercial greenhouses (Greenleaf and Kremen 2006b; Torres-Ruiz and Jones 2012), bumble bee efficacy (Kevan et al. 1991; Whittington and Winston 2004), and more recently whether greenhouses affect the health and productivity of commercially produced colonies (Colla et al. 2006; Morandin et al. 2002; Otterstatter and Thomson 2008; Whittington and Winston 2003a). Studies investigating the efficacy of bumble bees for greenhouse pollination have shown that not all bumble bee species are effective pollinators of tomatoes. For instance, Whittington and Winston (2004) investigated potential interspecific competition between *B. occidentalis* and *B. impatiens* in commercial tomato greenhouse operations. Their results showed that *B. impatiens* colonies produced more brood and workers, and made a greater number of foraging trips per hour than *B. occidentalis* colonies (Whittington and Winston 2004). *Bombus occidentalis* colonies did not appear to grow to their full potential size in tomato greenhouses, with fewer workers in greenhouse colonies than in colonies placed outside in a natural environment (Whittington and Winston 2004). *Bombus vosnesenskii*, a bumble bee species native to western Canada, also has potential to be an effective pollinator of tomatoes in greenhouses (Dogterom et al. 1998).

Several more recent studies have investigated whether greenhouses affect the health and productivity of commercial bumble bee colonies (Morandin et al. 2001c, 2002; Whittington and Winston 2003a). For example, Morandin and colleagues (2002) examined whether polyethylene coverings might affect commercial bumble bees in greenhouses. After measuring bee activity in four small greenhouses, each with a different polyethylene covering, these authors found no differences based on covering type (Morandin et al. 2002). Furthermore, investigations into the impact of pathogens, such as *Nosema bombi*, on commercial *B. occidentalis* colonies have found this pathogen to be detrimental to colony success and that infections in commercial greenhouse colonies can lead to pathogen spillover into wild populations (Colla et al. 2006; Otterstatter and Thomson 2008; Whittington and Winston 2003b). Predictive models suggest that during the first three months of such pathogen spillover, transmission from commercial hives would infect up to 20% of wild bumble bees within 2 km of greenhouse operations (Otterstatter and Thomson 2008).

Although commercially reared bumble bee colonies are the primary pollinator for greenhouse tomatoes, we also found evidence that honey bees may be a feasible alternative or supplement to bumble bee pollination (Higo et al. 2004; Sabara and Winston 2003). Comparing foraging from colonies within either screened or unscreened greenhouses, Sabara and Winston (2003) found that patterns of flower visitation were not influenced by screening either over the course of each day or the entire duration of the experiment. The addition of honey bee colonies to greenhouses already containing bumble bees caused no increase in the size of tomatoes produced (Higo et al. 2004). However, in another greenhouse in the same study the presence of honey bees produced significantly larger tomatoes when compared with greenhouses stocked only with bumble bees (Higo et al. 2004). Collectively these studies demonstrate the need for further investigation into the value of using of honey bees in greenhouse operations, either in combination with fewer bumble bee colonies, or as sole pollinators of greenhouse tomatoes.

We found significantly fewer studies investigating greenhouse pepper pollination when compared to the number of studies investigating greenhouse tomato pollination. One study from Ontario examining pollination effectiveness of *B. impatiens* for greenhouse sweet peppers showed there was a significant effect of bumble bees as pollinators for fruit weight, fruit width, and fruit volume for one cultivar 'Plutona'. For the other cultivar, 'Cubico', pollination by bumble bees significantly reduced the number of days from fruit set to harvest and increased the percentage of large and extra-large fruit (Shipp et al. 1994). Another study from Europe compared the efficacy of honey bees and bumble bees as pollinators of greenhouse grown sweet peppers (Dag and Kammer 2001). Their results suggest that the average yields for honey bee and bumble bee plots were similar. The presence of either honey bee or bumble bee colonies led to significant increases in the number of Grade A fruits produced compared to control conditions (no pollination: Dag and Kammer 2001). These results provide a further demonstration of the potential use of honey bees for pollination of greenhouse crop. Further investigation is warranted.

### Other Crops

Ginseng, a slow growing perennial plant mostly harvested for its roots, is grown almost exclusively in Ontario (accounting for 98.6% of Canadian production: Figure 14). We found established but incomplete evidence to support its pollination requirements provincially and nationally. While it is suggested that insect activity can lead to the occasional cross-pollination of ginseng (Woodcock 2012), it is generally considered to be a

parthenocarpic (self-fertile) crop. In fact, Carpenter et al. (1982) and Schluter and Punja (2000) have found that plants are fully self-fertile, and sometimes show that enhanced fruit set is achieved with pollination exclusion.

Common buckwheat (*Fagopyrum esculentum*: Polygonaceae) crops in Ontario account for approximately 2,552 hectares and less than 25% of Canada's total crop production (Figure 14: Statistics Canada 2012a). Buckwheat is a widely cultivated crop in North America and requires animal pollination (Klein et al. 2007). We found no studies investigating buckwheat pollination in Canada, including Ontario. However, we did find studies examining buckwheat pollination from the USA and Europe. The crop is primarily pollinated by honey bees (Bjorkman 1995; Grigorenko 1979), but flowers are often visited by numerous pollinators (Bartomeus et al. 2014; James et al. 2014; Taki et al. 2010). For example, a study completed by James et al. (2014) investigated beneficial insects attracted to several buckwheat species in central Washington. They found that a range of buckwheat cultivars attracted different species, further suggesting the potential of buckwheat as a component of habitat restoration strategies. Results from James et al. (2014) are similar to previously published literature demonstrating that both managed and wild pollinators are important for buckwheat pollination (e.g., Taki et al. 2010), and also suggests that crop yields are increased with proximity of natural and semi-natural habitat (Hendrickx et al. 2007; Hoffmann and Kwak 2007; Rands 2014; Steffan-Dewenter 1998).

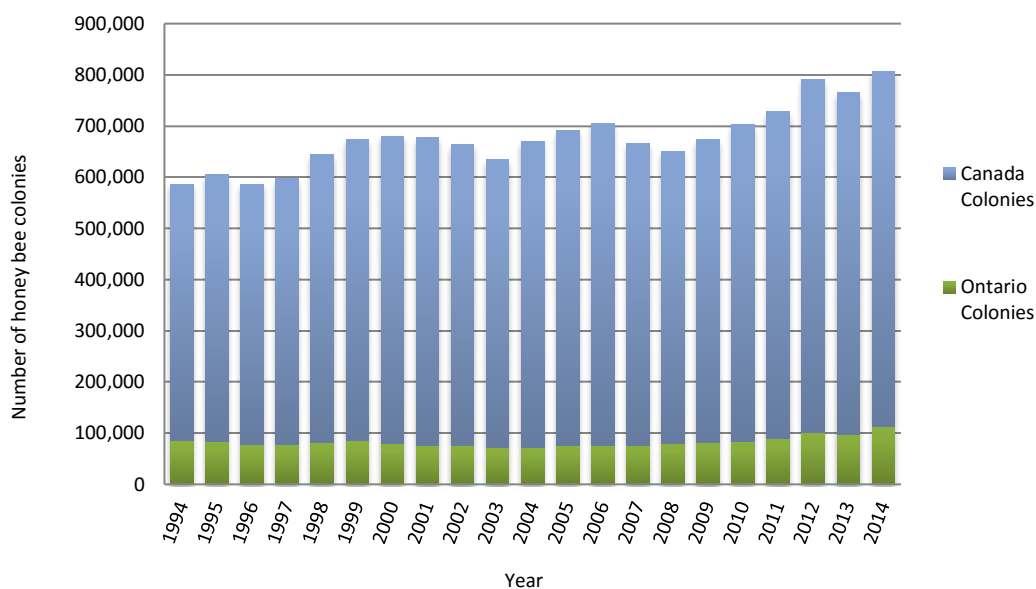
### **Ontario Honey Production**

In addition to contributing to pollination for a wide range of crops and wild plants, honey bees also add to the economy through the production of honey and other hive products, such as pollen, wax, propolis, and royal jelly. In 2014, 3,262 beekeepers kept one or more honey bee colonies in Ontario making a total of 112,800 colonies (OMAFRA 2014a: Statistics Canada 2015a: Figure 15). At the end of the 2014 season, Ontario represented 37.2% of Canada's beekeepers and 16.2% of Canadian wide colonies. Over the past 10 years the number of colonies in Ontario has increased by 32.7% (Figure 16).

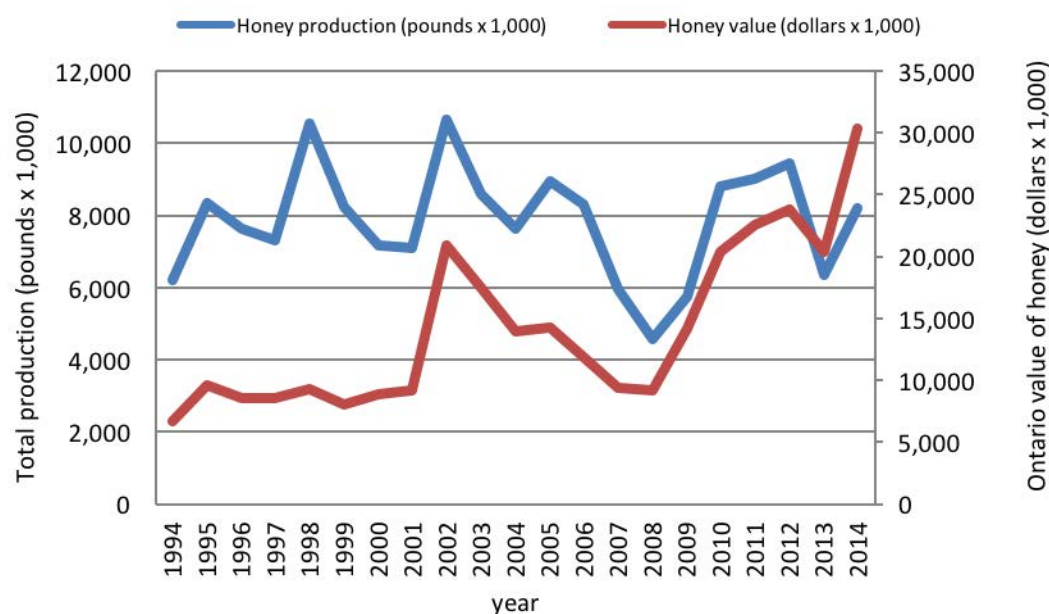
In 2014, Ontario's honey production was calculated at 8.2 million pounds, representing 10% of Canada's total production (Figure 17). Honey production in the province has fluctuated substantially over the past 10 years, but the value of honey has experienced substantial overall growth. In 2014, the value per pound of Ontario honey was \$3.70 compared to the national average of \$2.47. Canada is a net exporter of honey, exporting \$59 million in 2013, and importing \$26 million (Statistics Canada 2013). The USA is the largest export destination for Canadian honey, accounting for 77% of all honey exports. Japan and China are the second and third largest export destination respectively. Canada imported over \$8.6 million in honey from Argentina, followed by Brazil and New Zealand with imports of \$3.8 and 3.7 million worth of honey respectively (Statistics Canada 2013). Ontario however imports significantly more honey than it exports. In 2013, Ontario imported 64.9% of Canada's total honey imports. Ontario exported 18.8% of its production compared to the national average of 11%.



**Figure 15.** Map showing locations of honey bee colonies in Ontario (OMAFRA 2014a).



**Figure 16.** Total numbers of Ontario and Canada honey bee colonies over a 20-year period (1994-2014: Statistics Canada 2014a).



**Figure 17.** Total production of Ontario honey (pounds x 1,000) and its corresponding market value (dollars x 1,000: Statistics Canada 2014a).

### Other Hive Products

There is speculative evidence on the impacts of honey bee health on the provision of hive products (pollen for nutritional supplements, cosmetics, propolis, royal jelly).

### Pollen

Pollen is an important source of protein and lipid for bees, and is essential to larval growth and development. Foraging worker honey bees bring pollen from floral resources back to the hive, where it is passed to other worker bees, which combine the pellets with honey and bee secretions and store them in brood cells. Some beekeepers use devices to trap plant pollen from honey bees before they enter the hive. Although the exact chemical composition of pollen depends on the plants from which workers gather pollen, and consequently varies seasonally and from colony-to-colony, on average pollen contains around 37% carbohydrate, 20% proteins, and 6% lipids among other things (Almeida-Muradian et al. 2005). It is used as a human nutritional supplement, but evidence of health benefits varies (Kroyer et al. 2001; Nakajima et al. 2009). The effects of pollen trapping on honey bee colonies has been moderately studied, with contradictory results. McLellan (1974) reported that pollen trapping had no significant effect on the amount of brood reared, whereas Eckert (1942) and Webster et al. (1985) found that continuous pollen trapping reduced the amount of brood reared. McLellan (1974) reported a slight reduction in winter survival of colonies being trapped. For this reason, pollen trapping with high efficiency traps should never extend beyond a few days to prevent compromising colony health and strength.

### Propolis

Propolis is a product derived from plant resins collected by honey bees. It is used as a building material and for hive insulation (Greenaway et al. 1990). Propolis is used in traditional medicine and has antimicrobial properties (Grange et al. 1990; Stepanović et al. 2003). Chemical analysis has found at least 300 compounds in its composition, but is

primarily composed of resin (50%), wax (30%), essential oils (10%), and a small percentage of pollen (5%) and other organic compounds (5%: Castro 2001).

There is speculative evidence to support the impacts of extracting propolis on colony health. Simone-Finstrom and Spivak (2010) report that the incorporation of antimicrobial compounds in propolis may provide colony-level defence against pathogens. Among honey bee colonies, there is considerable variation in resin collection and propolis use (Manrique and Soares 2002; Page et al. 1995; Seeley and Morse 1976). For example, feral colonies nesting in tree cavities coat the entire inner walls with a thin layer of propolis forming what is referred to as a 'propolis envelope' around the nest interior (Seeley and Morse 1976). Propolis is added continuously to the nest wall during colony development, and is laid down in areas prior to comb attachment, which creates a clean surface and helps to reinforce new comb (Seeley and Morse 1976; Visscher 1980). Both feral colonies and managed colonies in commercial hive boxes generally use propolis for covering holes and crevices in the nest, and narrowing the hive entrance (Ghisalberti 1979). Propolis contributes to the reduction of microbial growth on hive walls, prevents uncontrolled airflow into the nest, waterproofs walls against sap (tree cavity nesting) and external moisture, in addition to creating some protection against invaders (Ghisalberti 1979; Seeley et al. 1976; Visscher 1980). Consequently, harvesting excessive amounts of propolis in a hive could put it at risk to moisture and pest exposure, and thus reduce colony strength.

### **Royal Jelly**

Royal jelly is one of the most valued products of honey bee colonies. It is produced from the hypopharyngeal and mandibular glands of 6-12 days old workers, referred to as nurse bees (Deseyn and Billen 2005; Hassan and Khater 2006). It is a creamy white substance consisting of water (50-60%), carbohydrates (15%), lipids (3-6%), mineral salts (1.5%) and vitamins for human consumption (Nagai et al. 2004). There is speculative evidence that royal jelly stimulates and strengthens the human immune system, and may be an assistant cure for many diseases such as leukemia, cancer, high blood pressure, high cholesterol, and infertility in males and females (Krell 1996; Pavel et al. 2011). Royal jelly has several uses such as feeding worker and drone larvae, and feeding queens both during larval development and as adults (Wang and Moeller 1969). Consequently, harvesting royal jelly from colonies would delay the production and development of larvae, and could weaken the colony due to the added stress put on nurse bees.

### **Crop Susceptibility to Pollinator Declines**

Pollinator declines are only likely to cause significant agricultural limitations for crops that are pollinator dependent, environmentally limited, and are incapable of self-pollination (Figure 18). Ghazoul (2005a) assessed the agricultural impact of pollinator declines and concluded that crop yields most reliant on specialist pollinators (e.g. field tomato) were most vulnerable whereas vegetative crops, which may propagate via self-pollination, were least vulnerable.

In Ontario, vegetative crops such as carrot and potato, are not considered key agricultural crop types, but rather are grown in urban gardens and at small agricultural scales. These crop types are least vulnerable to pollinator declines due to their ability to propagate via tubers, and self-pollination is only needed for seed distribution (Ghazoul 2005a). Wind pollination, commonly referred to as anemophily, is a form of pollination whereby pollen is distributed by wind (Shukla et al. 1998). Production of wind pollinated plants, such as corn and grains, including wheat and rice, is also at minimal risk due to pollinator declines.



The vulnerability of the remaining crops however, depends on the cultivar used/or the environmental conditions in which they are planted. For example, most cultivars require increased physical agitation to release pollen, which can be accomplished by wind and/or buzz pollination (McGregor 1976). Consequently, under ideal weather circumstances, some crop types such as field pepper cultivars, would be less vulnerable to pollinator declines. However, in less open areas wind alone may not be able to provide sufficient agitation, and thus pollinators can become more important.

The majority of key agricultural crops in Ontario are self-compatible to varying extents. Some species (e.g., peanut, ginseng) or cultivars of plants (e.g., canola, tomato, cucumber) are parthenocarpic, meaning that they do not need pollination to produce fruit. Cultivars of these plant species were created, and are commonly preferred by growers, to use under row covers and greenhouses, where there are few bees or other pollinators available. Others are self-compatible, although animal pollination improves the quality and quantity of yield (e.g., sunflower, green bean, raspberry, blackberry: Delaplane et al. 2000). Other plant species are self-compatible and wind pollinated, but production of marketable fruit is dependent on insect visitation (e.g., watermelon, tomato, blueberry cultivars, buckwheat). Commercially grown self-incompatible crop types that rely on animal pollination in Ontario include many field and fruit vegetables and orchard crops within the Rosaceae family (e.g., apple, pear, plum, sweet and sour cherry). These animal pollinated crops are generally intensively managed and grown at large-scales with applications of agrochemicals (e.g., insecticides, fungicides and herbicides). The intensive farming practices in these agricultural settings create immense demand for pollinator services, while simultaneously applying fertilizers and irrigation to supplement nutrient depletion. Under such conditions, even if native pollinators were at healthy population levels, pollination limitation may still be expressed. For example, 80% of the world's almonds are grown at large scale on around 6,800 farms in California. These orchards require pollination in February and early March, vastly outstripping the capacity of native pollinators to provide these ecosystem services, leading to influx of the majority of commercial US honey bee hives to California for this period (Macfarlane et al. 1995a; Morse and Calderone 2000). Pesticide use and the elimination of forage and larval food plants and nesting sites further exacerbates the issue in these settings (Banaszek 1992).

Self-incompatible plants can be limited environmentally and/or by the availability of required pollinators. The reproductive decline of the majority of wild plants is most likely attributable to spatial reductions in pollinator abundance, due to habitat loss and alterations (i.e., the inability of pollinators to move between isolated plants or populations in fragmented landscapes). Consequently, seed production of wild, non-crop, plants is likely to be more resource limited than for crop plants, for which landscapes can be anthropogenically enhanced through crop rotations and chemical fertilizers. Some researchers attribute the reproductive decline of wild plants to pollination failure (e.g., Potts et al. 2010), but few have been able to empirically show that pollination services are limited directly through declines in pollinator abundance and/or diversity (Ashman et al. 2004; Burd 1994; Ghazoul 2005b). Most agree that local depression of pollinator activity in natural environments is due to a limited capacity of pollinators to move between isolated resource patches in fragmented habitats (Potts et al. 2010). Consequently, seed production and the vulnerability of wild plant species is likely to be more resource limited than it is for crop plant species (which can be supplemented with fertilizers and irrigation methods).



Conversely, orchard fruit, currants, and many forage crops (clover, crown vetch, birdsfoot trefoil, canola) are self-incompatible and depend on generalist insect pollination. Crops which are self-incompatible and require specialist pollinators (e.g., tomato, blueberry and alfalfa cultivars) are most vulnerable to pollinator declines due to complex blooms whereby nectar or pollen is accessible only to specific pollinators. There are no key crops in Ontario that are wholly dependent on a single species for pollination services, although some species have much better efficacy in terms of pollination service provision. In the USA, Cane (2002) reported that female alfalfa leaf cutting bees excel at pollinating alfalfa, tripping 80% of visited flowers, compared to other effective unmanaged pollinators (Dylewska et al. 1970). Across North America, many native *Megachile* species can pollinate alfalfa well (Hobbs 1956, Bohart 1972), but typically they are not sufficiently abundant to satisfy the pollination requirements of this crop type (Pitts-Singer and Cane 2011), presumably due to the agricultural scales in which they are generally grown. Hence, alfalfa crops are particularly vulnerable to pollinator declines, due to their demand for relatively specialized pollinators.

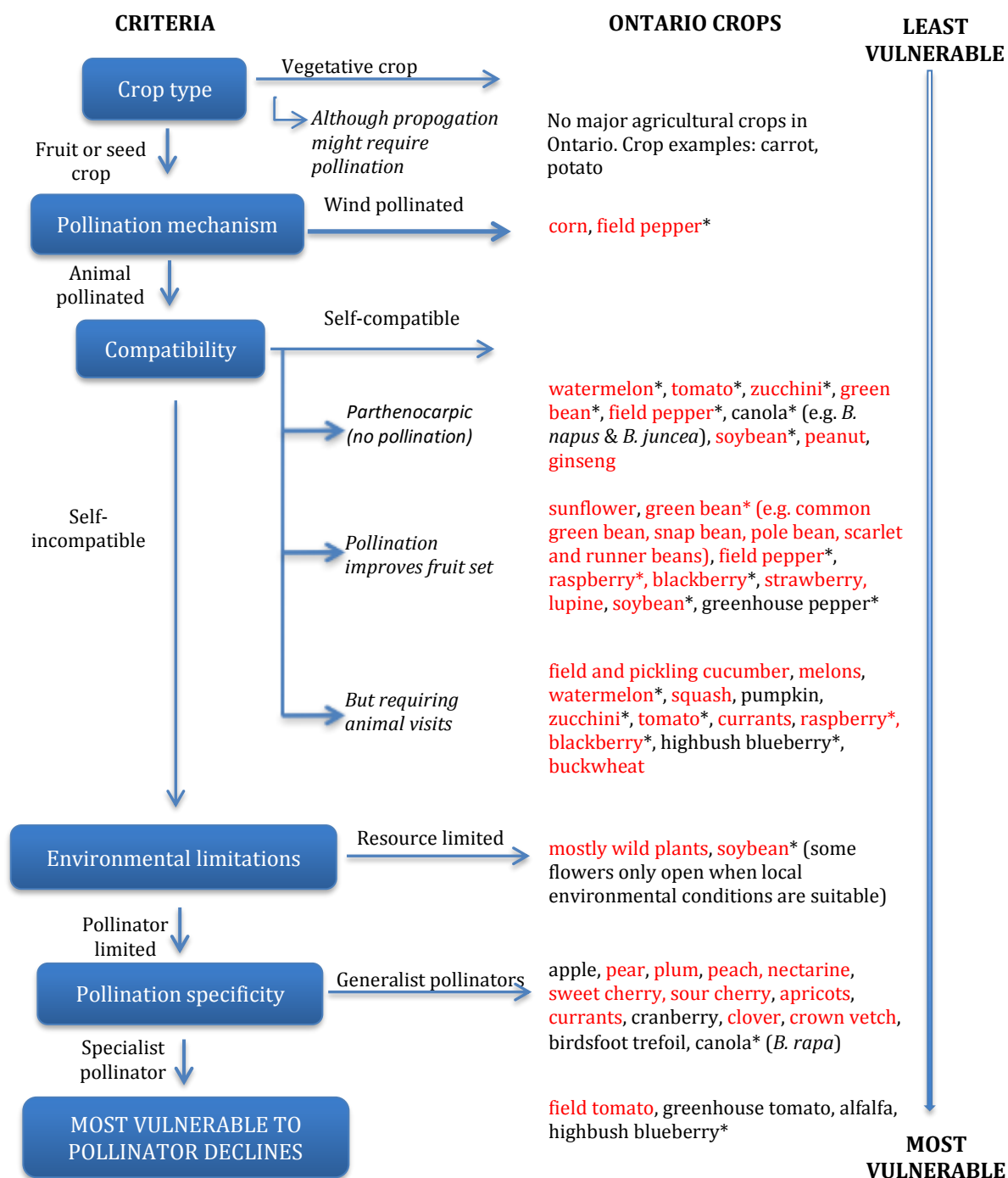
In summary, the susceptibility of crops in Ontario will be heterogenous, due to differences in land and crop management, and the availability of wild and managed pollinators in the landscape. Further research is needed to further understand the complexities involved in identifying the vulnerability of key crop types in Ontario, but this framework helps to identify the principal reproductive parameters involved.

### Suggestions

There remain significant knowledge gaps in our understanding of pollinators of key agricultural crops in Ontario. Furthermore, there is an appreciable disconnect between the economic value of crops and extent to which their pollination has been studied. More research is urgently needed to determine which pollinator species are present in agricultural crop systems and their value to pollination of the major crops produced in Ontario, such as soybeans, peas, beans, peaches, and sour cherry.

We recommend providing farmers with up-to-date information on the flight periods of key wild pollinators for specific crop types that are known to have increased fruit set with combined presence of both managed and wild pollinators.

Research is also needed to support the effective and sustainable use of other managed bee species for pollination alongside honey bee colonies, particularly for orchard fruits where evidence suggests that under favourable climatic conditions, managed wild bee populations should be considered for pollinator to increase fruit set.



**Figure 18.** The vulnerability of Ontario crops to pollinator declines (adapted from Ghazoul 2005a). Sensitivity of crops to pollinator declines is increased when the crop fulfills more criteria associated with its reproductive system. Crop types, which are reliant on specific pollinators, are expected to be vulnerable to pollinator declines, however in some circumstances this risk could be mitigated due to production in heavily managed systems (e.g. greenhouse tomato). Asterisks indicate variability among cultivars and varieties within crop types. Crops shown in red are those for which evidence of pollination requirements in Ontario are lacking. Woodcock (2012) was used to classify pollination requirements for crop systems.

## Pollination Services

Ecosystem services are ecological processes that are essential for human well being that are provided by nature for free (Daily 1997). These services include pollination, seed dispersal, water purification, and pest control (Luck et al. 2003). When the biodiversity of an ecological community declines, so too do the ecosystem services which it provides. Presently some of these critical services have been threatened because of the scale of anthropogenic activities (Díaz et al. 2006). Furthermore, it has been estimated that over the next several decades millions of plant and animal species will become extinct due human exploitation of their ecosystems (Cardinale et al. 2012; Hughes et al. 2002; Tscharntke et al. 2012).

Flowering plants have co-evolved with pollinators to generate producing a breathtaking diversity of floral strategies, pollinator adaptations and plant-pollinator interactions. Global estimates suggest 87.5% of all flowering plant (Angiosperm) species, and 78% in temperate regions such as Canada; have some reliance on animal pollination (Ollerton et al. 2011). Pollination in agricultural systems can be enhanced relatively easily through the use of managed pollinators. However, such approaches in natural ecosystem management are neither economically or logistically feasible (Mader et al. 2010). Hence, ensuring sustainable managed and wild pollinator populations are essential for maintaining managed and wild plant biodiversity (Fontaine et al. 2006; Ollerton et al. 2011) and consequently to ensure pollination services in these environments.

## **Summary of Evidence**

Pollination services are known to provide substantial benefits in agriculture as well as in natural environments. There is well established evidence supporting the value of pollination services provided by honey bees, and established but incomplete evidence to support the value added by other managed pollinators or wild bees in agricultural systems. Dependency ratios have been developed in the last 40 years to account for the value added by pollinators to agricultural crops, but these values vary considerably and the contributions to pollination from wild pollinators is vastly underestimated in many agricultural systems. Furthermore, there is considerable variation in value estimates for pollination services at regional and global scales, and no studies focusing on the value of pollination services at local scales. There is very little information on the identity and relative importance of pollinators of most rare plant species around world, which is cause for concern given that pollination is essential for the vast majority of flowering plants in natural environments. In Ontario, there are 78 plants listed as species at risk, for which pollination limitation may be a factor in their decline, however there are currently no-peer reviewed publications to support this view.

## **Economic Value of Crop Pollination Services in Agriculture**

Pollination services in agroecosystems contribute significantly to local, regional and global economies (Carreck and Williams 1998; Goulson 2003a). In recent decades, there have been numerous efforts to estimate the value of pollination services (Allsopp et al. 2008; Carreck and Williams 1998; Gallai et al. 2009; IPBES 2016; Lautenbach et al. 2012; Losey and Vaughan 2008; Winfree et al. 2011). Fundamentally, it is believed that quantifying the value of pollination services will encourage farmers, land managers and the public to protect pollinators and the free services they provide (Archer et al. 2014; Batáry et al. 2010; Melathopoulos et al. 2015).

In North America, there have been several efforts to quantify economic value of pollination services (CAPA 1995; Morse and Calderone 2000). In Ontario specifically, the combined populations of managed honeybees and bumblebees are said to generate about \$895 million of the roughly \$6.7 billion in sales for agricultural crops grown in the province each year (OMAFRA 2014b). This is a substantial increase from the estimate of honey bee contributions to Canadian agriculture that was valued at approximately \$443 million in 1995 (CAPA 1995). Furthermore in the US, the value of pollination services attributed to honey bee populations in 2000 was estimated at over \$14.6 billion (Morse and Calderone 2000), whereas in 2009 values were estimated at \$15 billion (Calderone 2012). On a global scale, there have also been several attempts at quantifying the value of pollination services (e.g., Costanza et al. 1997; Gallai et al. 2009; Pimentel et al. 1997) with the most recent estimate suggesting that pollination services enhance global crop production by \$235–577 billion US (based on 2009 market prices and production figures (Lautenbach et al. 2012), inflated to 2015 prices (Potts et al. 2016)). As such, this represents approximately 10% of the world's agricultural production value used for human food in 2005 (Gallai et al. 2009). Overall, we found substantial variations in estimates of the value of pollination services at regional and global scales. It should be noted that we found no study that quantified the value of pollination services at a local scale.

Our literature search also revealed that there have been two primary methods of assessing global pollination value. Used in the past, the first approach merely assesses the total value of insect pollinated crops (Martin 1975; Metcalf et al. 1962). The second approach, and more recently used method, involves using a dependence ratio that takes into account the impact of insect pollinators on crop production (Carreck et al. 1998; Morse et al. 2000). Specifically, the dependence ratio ( $D$ ) is used to determine the crop production loss if there is a total loss of insect pollination (Gallai et al. 2009; Winfree et al. 2011). That is, the economic pollination value is directly integrated with the loss of crop value. Several studies (e.g., Carreck et al. 1998; Gallai et al. 2009; Losey and Vaughan 2006) have calculated a pollination value using a dependency estimate. However, these published works have all employed a wide range of dependency values for the same crops (Allsopp et al. 2008; Carreck et al. 1998; Losey and Vaughan 2008) resulting in varying estimates of the value of pollination services.

A study by Melathopoulos and colleagues (2015) reported our capacity to quantify the risk of lost agricultural value due to wild pollinator loss is severely compromised, due to our current inability to assess the magnitude and importance of pollination services being provided by wild bees. Specifically, the authors argue that (1) true dependency of crop yields on insect pollination is relatively unknown; (2) the proportion of pollination dependency by wild pollinators is assumed in calculations; and (3) the loss of pollinators directly impacts the yields of the crops. Below we will expand on evidence found on each of the assumptions presented by Melathopoulos et al. (2015).

In table 8 (below), we illustrate how using different published  $D$  values (CAPA 1995; Klein et al. 2007) can produce rather divergent estimates of pollination value for key agricultural crops found in Ontario. These published sources were chosen as: (1)  $D$  values from CAPA (1995) were used as the basis for OMAFRA's calculations of pollination value (OMAFRA, 2014), and (2) the majority of global efforts to calculate valuations of pollination services have come to rely on  $D$  values derived from Klein et al. (2007). The annual value pollination services to apple and peach crops using CAPA's (1995)  $D$  resulted in estimates varying significantly above (+\$78 million) and below (-\$9 million) the average estimated

annual crop value (\$48 million for apple and \$17 million for peach) calculated using dependency information from Klein et al. (2007: Table 8). We also found substantial discrepancies in crop value estimates for canola and soybean crops. Using *D* from CAPA (1995) the annual value attributable to insects for canola pollination was estimated at \$0.5 million; whereas the annual value using *D* from Klein et al. (2007) was \$1.6 million (Table 8). However, the most substantial differences were in annual values of pollination to soybean crops where we found no reported *D* for CAPA (1995) and a *D* of 0.65 in Klein et al. (2007) resulting in an annual value attributable to insects of \$80 million (Table 8). This considerable difference in annual values is concerning when over 55% of Canada's soybeans are grown in Ontario and an estimate of their potential dependency on pollinations could be over \$80 million every year. Overall, it is evident that even slight variations in *D* values can distort estimates of pollination value at national and global scales. More research is needed to assess pollinators on many cultivars, grown in many fields over several localities and assessed across multiple seasons in order to fully understand the intricacies of crop dependency.

**Table 8.** Average crop yield estimates from 2009-2014 and annual value of pollination services to key agricultural crops in Ontario. Annual value of pollination services were quantified using CAPA (1995) and Klein et al. (2007) estimates of crop dependence on pollinators. Values in bold type indicate significant variations in annual value of pollination services per crop.

Crop	V = ON Mean value (\$'000): 2009–14	D = Dependence on insect pollination (CAPA 1995)	D <sub>Ave</sub> (D <sub>Min</sub> –D <sub>Max</sub> ) D <sub>Ave</sub> Average, D <sub>Min</sub> Min & D <sub>Max</sub> Max values of dependence on insect pollination (Klein et al. 2007)	V x D x D <sub>CAPA</sub> Minimum annual value attributable to insects (\$'000)	V x D x D <sub>Ave</sub> (D <sub>min</sub> – D <sub>max</sub> ) Average, minimum & maximum annual value attributable to wild bees (\$'000)
<b>Field Fruit and Vegetables</b>					
Cucumbers	16,355	1	0.65 (0.4-0.9)	15,357	9,982 (6,143-13,821)
Melon	15,357	1	0.95 (0.9-1)	19,478	18,504 (17,530-19,478)
Watermelon	19,478	1	0.95 (0.9-1)	27,036	25,684 (24,332-27,036)
Pumpkin	27,036	1	0.95 (0.6-1)	11,627	11,046 (10,465-11,627)
Peas	11,627	-	-	-	-
Green beans	45,324	-	0.05 (0-0.1)	-	2,732 (0-5,463)
Dry Bean	54,634	<b>0.5</b>	<b>0.05 (0-0.1)</b>	-	-
Tomatoes	301,962	0.8	0.05 (0-0.1)	-	15,098 (0-30,196)
Peppers	19,631	0.8	0.05 (0-0.1)	-	982 (0-1,963)
<b>Orchard Fruit</b>					
Apple	74,541	<b>1</b>	<b>0.65 (0.4-0.9)</b>	<b>74,541</b>	<b>48,452</b> <b>(29,816-67,087)</b>
Pear	3,265	1	0.65 (0.4-0.9)	3,265	2,122 (1,306-2,938)
Plums	4,053	0.8	0.65 (0.4-0.9)	3,242	2,634 (1,621-3,647)
Sweet Cherry	1,778	1	0.65 (0.4-0.9)	1,778	1,156 (711-1,600)

## Status and Trends of Pollinator Health in Ontario

Sour Cherry	5,127	0.7	0.65 (0.4-0.9)	3,589	3,333 (2,051-4,615)
Apricots	146	0.7	0.65 (0.4-0.9)	102	95 (59-132)
Peach	26,971	<b>0.35</b>	<b>0.65 (0.4-0.9)</b>	<b>9,440</b>	<b>17,531</b> <b>(10,788-24,274)</b>
<b>Berries</b>					
Currant			0.25 (0.1-0.4)	-	-
Raspberry	3,849	0.9	0.65 (0.4-0.9)	3,464	2,502 (1,540-3,464)
Strawberry	19,698	0.3	0.25 (0.1-0.4)	5,910	4,925 (1,970-7,879)
Blueberry (Highbush)	4,721	1	0.65 (0.4-0.9)	4,721	3,069 (1,888-4,249)
Cranberry	473	1	0.65 (0.4-0.9)	473	307 (189-426)
<b>Oilseed and forage</b>					
Alfalfa (seed)	109,000	1			
Clover (seed)	-	1	-	-	-
Vetch	-	-	-	-	-
Trefoil	-	-	-	-	-
Lupine	-	-	-	-	-
Canola	2,566	<b>0.2</b>	<b>0.65 (0.4-0.9)</b>	<b>513</b>	<b>1,668</b> <b>(1,026-2,309)</b>
Sunflower	455,000	0.2	0.1 (0.1-0.4)	91,000	113,750 (45,500-182,000)
Soybean	123,060	-	<b>0.65 (0.4-0.9)</b>	-	<b>79,989</b> <b>(29,224-110,754)</b>
Peanut	109,000	-	-	-	-
<b>Greenhouse crops</b>					
Tomato	295,768	-	-	266,192	-
Pepper	194,288	-	-	174,860	-
<b>Other</b>					
Ginseng	-	-	-	-	-
Buckwheat	-	-	-	-	-
<b>TOTAL ALL</b>				541,728	365,561 (186,159-524,958)

There is some evidence to support how wild species contribute to crop pollination, and what percentage of crop pollination results from visits of unmanaged bee species (Breeze et al. 2011; Kremen 2008; Quaranta et al. 2004; Steffan-Dewenter 1998; Winfree et al. 2007a, 2008). However, we do not yet have a clear understanding of the true dependency of crop yields on insect pollination. The majority of the pollination value calculations conducted to date assume the proportion of pollination dependency by wild pollinators. Furthermore, several studies in the USA have shown that wild bees may be able to provide insurance for full or partial failure of the pollination services provided by managed pollinator species (Hall and Ascher 2011; Winfree et al. 2007a, 2008). Similarly, studies from Europe have demonstrated that pollination services provided by insects, other than honey bees, have become increasingly important to agriculture (Breeze et al. 2011; Garratt et al. 2014; Westphal et al. 2003). However, when determining the annual value of crops, perhaps the principle issue is that the proportion of yields attributable to wild pollinators is rarely, if at all, associated with any research on the activity of wild bees in various agriculture systems (Melathopoulos et al. 2015). We found no studies from Canada, including Ontario investigating the contribution of wild bees in any agricultural systems. Given pollinators

have been estimated to generate about \$895 million in sales for agricultural crops in the province each year (OMAFRA 2014b), more research is needed into the activity of wild bee populations in agriculture systems in order to fully understand the yields attributable to wild species.

In many of the published estimates of pollination value found (e.g., Allsopp et al. 2008; Carreck et al. 1998; Gallai et al. 2009; Losey and Vaughan 2008; Winfree et al. 2011), it is assumed that declines in pollinators are directly associated with decreases in agricultural value. Even though many studies have shown crop yields increase with the presence of greater pollinator species richness (Garibaldi et al. 2014; Chaplin-Kramer et al. 2011; Meadows 2011; Thorp 2012; Winfree and Kremen 2009), very few studies have tested whether crop yields actually decline with the loss of species. It has also been suggested that it is highly unlikely all pollinator taxa would decline throughout a given region or across multiple regions (Melathopoulos et al. 2015). We did find one Canadian study that examined the impact of bee pollinator collapse on lowbush blueberry yield by comparing pollination success by day or night (Cutler et al. 2012). Although fruit set in this insect dependent crop (Isaacs and Kirk 2010; Ratti et al. 2008) was higher for blueberry stems available to flower visitors during the day, Cutler et al. (2012) also reported significant fruit set from stems exposed only at night. Blueberries pollinated by day or night were similar in weight, suggesting that non-bee pollinators active at night may contribute significantly to fruit set in lowbush blueberries in Nova Scotia, potentially helping mitigate the effects of pollinator decline. More research investigating nocturnal pollination, and pollination by non-bee taxa (e.g., Rader et al. 2016), is warranted.

### **Landscape Considerations to Optimize Pollination Services in Agriculture**

Agricultural cropland can have either a positive or negative effect on pollinator communities and the services they provide, depending on the spatial scale, and intensity of agricultural land use (Steffan-Dewenter et al. 2008; Tscharntke et al. 2005). We found no studies from Ontario investigating regional or landscape scale impacts on pollination services in agri-environments. This is concerning given that in Ontario areas of native habitat continue to decline as a result of ongoing agricultural intensification, urbanization, and other anthropogenic land-use change, to the point it is possible that many habitat patches may no longer support sizeable or diverse native bee communities.

There is however, well established evidence from the USA and Europe investigating the impact of forage and nesting resources in close proximity to agricultural fields (Holzschuh et al. 2008; Lowenstein et al. 2012; Steffan-Dewenter, 1998, 2001; Winfree et al. 2008). For example, Kremen (2008) reported that both site and landscape scale factors are important to pollinators (Figure 19). To demonstrate the influence of landscape scales on pollinator diversity and abundance in agricultural systems, many studies assess bee biodiversity metrics (diversity, richness and abundance) at various radii (typically 250, 500, 750, 1000 and 1250 m) from the centre of agricultural fields (e.g., Holzschuh et al. 2008; Ricketts et al. 2008; Steffan-Dewenter et al. 2001) to include the flight ranges of most bees based on their size (Gathmann and Tscharntke 2002; Greenleaf et al. 2007). For example, Ricketts and colleagues (2008) completed a meta-analysis of 23 published studies - representing 16 crops on five continents - to estimate the overall relationship between pollination services and distance from natural or semi-natural habitats. The authors successfully demonstrated that pollinator visitation rates declined steeply when natural habitat was more than 0.6 km away from agricultural crops, and that species richness

significantly declined when natural habitat was more than 1.5 km from agricultural crops (Ricketts et al. 2008).



**Figure 19.** Adapted from Kremen (2008) depicting the importance of landscape and agricultural scale influences in a landscape. The small green box denotes a farm field within a larger (generally heterogenous) landscape. The x denotes the nesting site of 2 female bees – one nesting within the agricultural field, and the other not. In both cases, bee foraging ranges (red circles) encompass both agricultural and non-agricultural areas.

In California, Kremen and colleagues (2002b) examined the role of native wild bees in crop pollination, and how the services they provide are altered as environmental conditions become less favorable. They found that native bees made up a higher proportion of total flower visits, suggesting they can be as or more important than managed honey bees if proximity to natural or semi-natural land is taken into consideration (Kremen, 2008). Several studies also reported similar results that abundance within bee guilds is influenced differently by a range of landscape parameters and land cover (Hopfenmüller et al. 2014; Lautenbach et al. 2012; Ricketts et al. 2008; Tscheulin et al. 2011). For example, Hopfenmüller et al. (2014) specifically tested the importance of habitat area, quality and connectivity as well as landscape composition and configuration on wild bees communities. Their results revealed strong dependence of habitat bee specialists on local habitat characteristics. That is, cleptoparasitic bees and bumble bees are more likely affected by the surrounding landscape compared to social generalist species (Hopfenmüller et al. 2014).

Furthermore, at the landscape scale, habitat composition (heterogenous/homogenous environments) influences the diversity and abundance of forage and nesting sites and substrates within bee species flight ranges. As an example, Jha and colleagues (2013) investigated the impact of habitat heterogeneity and floral resource distributions on nesting and foraging patterns of *Bombus vosnesenskii*. Their study reported that bumble bees forage further than once thought to find flower patches and in landscapes where patch-to-patch variation in floral resources is less, regardless of habitat composition (Jha et al. 2013). These results are also consistent with a study from Europe that used translocation experiments to determine foraging distances and measured foraging trip duration to demonstrate how solitary bees cope with the distance between nesting sites and suitable



food plants in various habitat patches (Gathmann and Tschardt 2002). Their results showed that solitary bees have small foraging ranges and local habitat structure seems to be of more importance than large-scale landscape structure.

### **Pollination Services of Wild Plants**

It is predicted that pollinator declines will cause populations of native plants to decline (Potts et al. 2010), putting them at risk of extinction. Indeed, where quality data sets have been compiled, such as in the Mediterranean, local plant diversity appears to have declined in most sites and in most habitats (Lavergne et al. 2006). There is evidence from the UK that 76% of forage plants used by bumble bees declined in frequency between 1978 and 1998 (Carvell et al. 2006). Habitat loss and fragmentation has been documented to increase the risk of local plant population extirpation, through inbreeding, genetic drift and other stochastic processes (Kevan and Viana 2003). Furthermore, pollinator limitation has been shown to reduce seed output by 50-60% in rare plants found in fragmented landscapes (Pavlik et al. 1993; Vaughan 1995). The IUCN predicted a global loss of 20,000 flowering plant species within the next few decades, consequently leading to the vulnerability and declines of plant-pollinator networks and services (Heywood 1995).

In Ontario, there are 78 conservation status listed plant species for which pollination limitation may be a factor in their decline (Table 9), however there is established but incomplete evidence to support this. Little is known about the pollinators of rare plants, which is a cause for concern given that pollination is essential for the long-term survival of most flowering plant species. Gibson and colleagues (2006) looked at pollinator webs and the conservation of three rare plant species in the UK. They found that all three species of rare plants were linked to other plant species in the community by shared pollinators. They suggest that at least in some cases, that the long-term survival of rare plant populations is likely to depend on the more common plant species in the community. Thus, the management of rare plants, at least in some cases, should also include the protection and management of populations of some of the more common plant species in their respective communities. Although provincial and federal governments identify the importance of pollinators, such as bees, as playing a key role in the survival for many of Ontario's rare plants (e.g. <http://www.ontario.ca/environment-and-energy/cucumber-tree-species-risk>) results from our systematic literature review found no peer-reviewed or grey literature to support this.

The ecological importance of wild bees and other pollinators in ecosystems is critical. If a keystone plant species loses its pollinators, the entire structure of the biotic community (plant and animal) could be dramatically and irreversibly altered. A well-known example are fig trees (*Ficus* spp.) for which fruit set is highly dependent on the specialized pollination by minute fig wasps (Hymenoptera, Chalcidoidea, Agaoninae: Berg 1989). Each of the approximately 750 species of fig tree (Berg 1989) is typically pollinated by a single species of fig wasp, which is uniquely associated with that tree species (Michaloud et al. 1988; Wiebes 1979). Fig trees are considered key-stone species in many tropical ecosystems due to their integral role in forest structures, and the production of fruit consumed by birds and mammals (Terborgh 1986). Consequently, losing these fig wasp species would likely have a major effect on the structure and function of tropical forests (Nason et al. 1998).

**Table 9.** Conservation status plants of rare plants in Ontario

Common Name	Scientific name	Status
American Chestnut	<i>Castanea dentata</i>	Endangered
American Columbo	<i>Frasera caroliniensis</i>	Endangered
American Ginseng	<i>Panax quinquefolius</i>	Endangered
American Water-willow	<i>Justicia americana</i>	Threatened
Bashful Bulrush	<i>Trichophorum planifolium</i>	Endangered
Bent Spike-rush	<i>Eleocharis geniculata</i>	Endangered
Bird's-foot Violet	<i>Viola pedata</i>	Endangered
Blue Ash	<i>Fraxinus quadrangulata</i>	Threatened
Bluehearts	<i>Buchnera americana</i>	Endangered
Blunt-lobed Woodsia	<i>Woodsia obtusa</i>	Threatened
Branched Bartonnia	<i>Bartonia paniculata</i> ssp. <i>paniculata</i>	Threatened
Broad Beech Fern	<i>Phegopteris hexagonoptera</i>	Special Concern
Butternut	<i>Juglans cinerea</i>	Endangered
Cherry Birch	<i>Betula lenta</i>	Endangered
Climbing Prairie Rose	<i>Rosa setigera</i>	Special Concern
Colicroot	<i>Aletris farinose</i>	Threatened
Common Hoptree	<i>Ptelea trifoliata</i>	Threatened
Crooked-stem Aster	<i>Symphyotrichum prenanthoides</i>	Special Concern
Cucumber Tree	<i>Magnolia acuminata</i>	Endangered
Deerberry	<i>Vaccinium stamineum</i>	Threatened
Dense Blazing Star	<i>Liatris spicata</i>	Threatened
Drooping Trillium	<i>Trillium flexipes</i>	Endangered
Dwarf Hackberry	<i>Celtis tenuifolia</i>	Threatened
Dwarf Lake Iris	<i>Iris lacustris</i>	Special Concern
Eastern Flowering Dogwood	<i>Cornus florida</i>	Endangered
Eastern Prairie Fringed-orchid	<i>Platanthera leucophaea</i>	Endangered
Eastern Prickly Pear Cactus	<i>Opuntia humifusa</i>	Endangered
Engelmann's Quillwort	<i>Isoetes engelmannii</i>	Endangered
False Hop Sedge	<i>Carex lupuliformis</i>	Endangered
False Mermaid	<i>Floerkea proserpinacoides</i>	Not at Risk
False Rue-anemone	<i>Enemion biternatum</i>	Threatened
Forked Three-awned Grass	<i>Aristida basiramea</i>	Endangered
Four-leaved Milkweed	<i>Asclepias quadrifolia</i>	Endangered
Gattinger's Agalinis	<i>Agalinis gattingeri</i>	Endangered
Goldenseal	<i>Hydrastis canadensis</i>	Threatened
Green Dragon	<i>Arisaema dracontium</i>	Special Concern
Hart's-tongue Fern	<i>Asplenium scolopendrium</i>	Special Concern
Heart-leaved Plantain	<i>Plantago cordata</i>	Endangered
Hill's Pondweed	<i>Potamogeton hillii</i>	Special Concern
Hill's Thistle	<i>Cirsium hillii</i>	Threatened
Hoary Mountain-mint	<i>Pycnanthemum incanum</i>	Endangered
Horsetail Spike-rush	<i>Eleocharis equisetoides</i>	Endangered
Houghton's Goldenrod	<i>Solidago houghtonii</i>	Special Concern
Illinois Tick-trefoil	<i>Desmodium illinoense</i>	Extirpated
Juniper Sedge	<i>Carex juniperorum</i>	Endangered
Kentucky Coffee-tree	<i>Gymnocladus dioica</i>	Threatened
Lakeside Daisy	<i>Tetraneuris herbacea</i>	Threatened
Large Whorled Pogonia	<i>Isotria verticillata</i>	Endangered
Nodding Pogonia	<i>Triphora trianthophoros</i>	Endangered
Ogden's Pondweed	<i>Potamogeton ogdenii</i>	Endangered
Pink Milkwort	<i>Polygala incarnata</i>	Endangered
Pitcher's Thistle	<i>Cirsium pitcheri</i>	Special Concern
Purple Twayblade	<i>Liparis liliifolia</i>	Threatened
Red Mulberry	<i>Morus rubra</i>	Endangered
Riddell's Goldenrod	<i>Solidago riddellii</i>	Special Concern
Round-leaved Greenbrier	<i>Smilax rotundifolia</i>	Threatened

Scarlet Ammannia	<i>Ammannia robusta</i>	Endangered
Short's Aster	<i>Symphyotrichum shortii</i>	Not at Risk
Showy Goldenrod	<i>Solidago speciosa</i>	Threatened
Shumard Oak	<i>Quercus shumardii</i>	Special Concern
Skinner's Agalinis	<i>Agalinis skinneriana</i>	Endangered
Slender Bush-clover	<i>Lespedeza virginica</i>	Endangered
Small White Lady's-slipper	<i>Cypripedium candidum</i>	Threatened
Small Whorled Pogonia	<i>Isotria medeoloides</i>	Endangered
Small-flowered Lipocarpa	<i>Lipocarpa micrantha</i>	Endangered
Spotted Wintergreen	<i>Chimaphila maculata</i>	Endangered
Spring Blue-eyed Mary	<i>Collinsia verna</i>	Extirpated
Swamp Rose-mallow	<i>Hibiscus moscheutos</i>	Special Concern
Toothcup	<i>Rotala ramosior</i>	Threatened
Tuberous Indian-plantain	<i>Arnoglossum plantagineum</i>	Special Concern
Virginia Goat's-rue	<i>Tephrosia virginiana</i>	Endangered
Virginia Mallow	<i>Sida hermaphrodita</i>	Endangered
Western Silvery Aster	<i>Symphyotrichum sericeum</i>	Threatened
White Prairie Gentian	<i>Gentiana alba</i>	Endangered
White Wood Aster	<i>Eurybia divaricate</i>	Threatened
Wild Hyacinth	<i>Camassia scilloides</i>	Threatened
Willowleaf Aster	<i>Symphyotrichum praealtum</i>	Threatened
Wood-poppy	<i>Stylophorum diphyllum</i>	Endangered

## Suggestions

There remain significant knowledge gaps in our understanding of the value of pollination services. Better measures need to be established to provide more accurate value estimates. Specifically, more research is needed to understand true dependency of crops on insect pollination, and whether the loss of pollinators directly impacts the yield or quality of crops. Further research into the activity of wild bee populations in agriculture systems is needed in order to fully understand the proportion of yields attributable to wild pollinator species. We found no studies that investigated the economic value of pollination services on a local scale, further investigation is warranted. We found no studies from Ontario investigating landscape scale factors and how they influence the diversity and abundance of forage and nesting sites for wild bees within average flight ranges of insect dependent agricultural crops. This is concerning given that in Ontario, with expanding agricultural intensification and modern farming practices, the size of native habitat areas are declining and it is possible that many can no longer support sizeable native bee communities. Very little is known about the pollinators of rare plants in Ontario, which is a cause for concern given that pollination is essential for the long-term survival of most flowering plant species. Research focusing on pollination limitation and the part it plays in contributing to rare plant species in Ontario is needed.

## **IMPACTS OF EXISTING POLLINATOR MANAGEMENT AND CONSERVATION STRATEGIES**

### **Executive Summary**

Currently, there is limited legislation in Ontario and Canada to protect pollinators. The Ontario Bees Act addresses solely honey bees, and often protects the rights and liabilities of beekeepers over the health of honey bees themselves. The Endangered Species Act also protects nine pollinator species at risk. Additional legislation, directed at both managed and wild species, could be helpful to protect pollinators in Ontario, Canada, and around the world. The most important consideration with creating new conservation policies and legislation are that they are based on rigorous scientific evidence, they are evaluated for their efficacy and revised as necessary to improve utility.

In an effort to protect pollinators, conservation strategies can be implemented in agricultural areas, urban environments, and other sensitive lands. Selection and implementation of specific strategies will depend on conservation priorities, and may differ substantially if the goal is to enhance pollination of particular crops, maintain wider pollinator biodiversity or specifically target the recovery of pollinator species at risk. The best conservation strategies may deliver more than one of these goals, and also provide suitable habitat for other beneficial arthropods (e.g. spiders and parasitoid wasps that can provide pest bio-control), birds and wildlife in the landscape.

Most research to date has focused on adding and restoring pollinator habitat, typically by planting more abundant and diverse floral mixtures, and providing or enhancing nesting sites and suitable larval host plants, and the evidence has shown these strategies can be highly effective at increasing pollinator abundance and species richness. Restoring established habitat, as well as generating new habitat through innovative means (e.g., creating pollinator gardens on old landfill sites or suitable habitat along roadsides, railways or under power lines) improve provision of pollinator forage and nesting sites. Evidence from USA and Europe suggest at a landscape scale that conservation strategies need to consider connectivity of suitable habitat patches at scales relevant to foraging and dispersal. These scale considerations are also likely to be important for enhancing crop pollination by wild pollinators. The lack of critical information on the distribution and biodiversity of pollinators in Ontario represents a major obstacle to developing appropriate and sustainable conservation strategies.

### **Pollinator Management and Conservation Strategies**

The wild pollinators of Ontario have adapted to the environments of this province, specifically co-evolving with native plant communities, and it is therefore important to conserve them to maintain the health, biodiversity and function of these important ecological systems. In addition to their vital ecological role of supporting native plant diversity, pollinators provide economically important crop pollination services that are essential for agricultural production and food security. During historical periods of agricultural expansion biodiversity conservation has been de-prioritised in favour of increasing crop yields through intensification of agriculture (associated with increased pesticide use, higher levels of monoculture, and conversion of natural land into farm fields). With the recent pollinator declines in Ontario, across Canada and around the world, new government policies and recommendations could help improve agricultural production and also protect biodiversity (Mineau and McLaughlin 1996). To prioritize both – and

maximize crop pollination as a result – suitable habitat within and surrounding these fields must be increased. Here we review evidence-based strategies that promote pollinators in agricultural land through habitat creation. It also includes pesticide management strategies and other agricultural practices that can be adjusted to improve pollinator health. Integrated pest management strategies offer a practical solution.

In addition to agriculture displacing pollinator habitat, urbanization has also been identified as a factor affecting bee populations (see page 36). Conservation strategies for pollinators in urban landscapes should be geared toward increasing overall green space, planting flowers attractive for pollinator forage, and increasing nesting resources. Due to the general lack of natural space in urban areas, these strategies often need to be developed and implemented in innovative and creative ways.

Lastly, the declining health of managed bees (honey bees, blue orchard bees, managed *Bombus*, and alfalfa leafcutter bees) is in part due to their management by humans. We will review how regularly monitoring bee health, treating (or failing to treat) for pests and pathogens, as well as best management practices all impact these species. Integrated pest management emerges again as a tool to best manage these pollinators. Providing adequate nesting sites and forage for managed bees also positively affects their conservation.

After the development of conservation strategies, it is necessary to evaluate their efficacy in increasing pollinator abundance, diversity and health. Monitoring populations (both before their implementation and after) is encouraged. An emerging conservation tool is developing pollinator networks that detail species-specific interactions between pollinators and plant species (e.g., Burkle et al. 2013; Gibson et al. 2006; Elle et al. 2012). Perturbations in these networks show which species are affected most by stress factors such as habitat alteration and climate change, and can provide clues as to which flower species provide good food sources for pollinators and should be planted. Pollinator networks can also predict what would happen if rare or endangered species populations were improved through translocation experiments. One simulation by LaBar and colleagues (2014) showed translocating extirpated species might successfully restore species richness. However, translocation experiments may not be successful in reality. If the factor that caused the species' decline in the first place are not known or dealt with, the translocated species may be susceptible to declines from this factor as well.

Europe has been the continent spearheading pollinator conservation strategies worldwide, and Ontario can learn a lot from their successes and failures. Their push for pollinator protection is due to the limited natural land remaining throughout Europe. Much of the countryside has been altered by human land use, and therefore there is a high priority to develop and implement conservation strategies to preserve what wildlife habitat remains (Batáry et al. 2015). For example, when the percent of agricultural land was last measured in the UK in 2012, it covered 71% of the total land area (The World Bank Group 2015). The United State's agricultural land was reported at 44%, and Canada's at 7.2%. Provinces like Ontario still have a lot of natural land, especially in the north. However, southern Ontario is heavily urbanized and agriculturally managed. Adopting agriculture-environment policies in Ontario that have proven to be successful in Europe could assist in conserving and rebuilding the natural habitats that declining pollinators rely on.

The goal in this section of the report is to outline the scientific rationale and evidence for success behind interventions and conservation strategies for pollinators from around the world. This will provide options for evidence-based strategies for pollinator management,

conservation and restoration, and provide the platform Ministry assessment of the economic and other factors affecting decisions to implement strategies. In this section of the report we will also highlight key scientific knowledge needs to allow the implementation of effective and sustainable pollinator conservation strategies in Ontario.

### **The Four Approaches to Conservation**

The scientific literature breaks down conservation tactics into four categories: (1) local-scale versus (2) large-scale conservation and (3) species-targeted versus (3) group-targeted conservation.

#### **Local-Scale Versus Large-Scale**

Local-scale conservation deals with strategies that happen at the property or individual land-owner scale (e.g., habitat creation and management on a single farm). Large-scale modifications are implemented at much wider geographic scales (e.g., heterogeneous habitat creation and management across an entire farming community). These scales are relative, rather than absolute, and can vary considerably depending on the area in question. In Canada, average farm sizes increases 30% in the 20 years to 2011 (from 598 to 778 acres: Statistics Canada 2014c), making the distinction between these two scales increasingly ambiguous.

Executing conservation strategy recommendations at a large-scale can be accomplished in agricultural land, urban areas, rights-of-way, and other land (e.g., restored landfills and brownfield sites). This can have the effect of increasing overall abundance of keystone species that often pollinate the majority of flowers, including many crops (Kleijn et al. 2015). To conserve rare species, that typically have more specific requirements for habitat and food, conservation strategies must focus on local-scale initiatives, such as preserving already known nesting sites, planting forage flowers that are specific to rare species, and increasing connectivity and dispersal between populations (Goulson et al. 2011). A meta-analysis examining the conservation strategies of agricultural land in 31 studies showed that both local-scale and large-scale strategies benefited pollinators. Local-scale conservation strategies include reducing fertilizer and pesticides, while large-scale strategies incorporate natural or semi-natural lands for habitat surrounding farm fields (Gonthier et al. 2014). The authors of this meta-analysis conclude by recommending policy makers to implement strategies at both the local- and large-scale.

#### **Species-Targeted Versus Group-Targeted**

Species-targeted conservation is geared toward improving conditions for rare and declining pollinators. This approach identifies habitats or regions in which remaining populations of these species are found, characterizes their ecological requirements, and then implements conservation strategies to target these species directly. Group-targeted conservation focuses on implementing changes for entire functional groups or habitat types. For example, prescribed burns benefit a vast majority of solitary and social ground nesting bees (Taylor and Catling, 2009). Similarly, restoring an entire habitat, such as a sand dune system, benefits a community of species that live within it. Research using pollination networks suggests conservation efforts that target certain species groups, (such as long-tongued bees that are in decline due to the rarity of deep corolla flowers: Corbet 2000) and keystone species that provide the most pollination (Cariveau and Winfree 2015), enhance ecosystem function more than strategies that target only rare species.

Species-targeted conservation employs the local-scale approach, while group-targeted conservation is usually implemented with a large-scale approach, but these relationships are not mutually exclusive. The most effective conservation strategies typically blend together these four approaches. In general, current conservation priorities for pollinators tend to focus on the group-level, simply because we do not have sufficient information on the ecological requirements of all individual species in Ontario (Mineau and McLaughlin 1996). However, it is risky, and potentially counterproductive, to assign regulations and guidelines without knowing the specific requirements of the species involved. A common theme emerging from the “Status and Trends of Pollinators in Ontario” section of this report (starting on page 23) is that different species and functional guilds can vary widely in their responses to environmental stressors. This suggests that species may also respond differently to the same conservation strategy. For example, mowing practices promote the growth of small flowers which benefit small-tongued bees, but eliminate deep corolla flowers that serve as the main food source for long-tongued bees (Corbet 2000). A multi-scale approach to improve overall habitat, with particular reference to declining keystone species, may therefore be an effective strategy to maintain pollinator populations and biodiversity.

### **The Importance of Connectivity**

Preserved habitats, such as provincial parks or natural meadows, serve as important refuges for pollinators. However, it is also essential there are corridors connecting them to facilitate pollinator dispersal (Casacci et al. 2015). Regions of connectivity expand usable habitat and provide linkages that connect isolated populations to enhance genetic diversity. Connectivity also maintains common pollinator diversity to prevent future declines. Establishing and maintaining pollinator habitat along field margins, rights-of-way, power line corridors, and roadsides can enhance connectivity. These corridors need not be in direct contact with each other, but the habitat “stepping stones” need to be within pollinator dispersal distances to enable gene flow.

### **Increasing Genetic Diversity Through Habitat Connectivity**

Genetic variation is reduced in populations that become isolated as a result of habitat loss and fragmentation (Gilpin 1991). Bees are particularly susceptible to population declines and extinction because of their (haplodiploid) genetic sex determination system. In short, reduced genetic diversity leads to the production of sterile males that cannot produce offspring for the next generation. It is likely that bee declines have been due to this reduced genetic diversity resulting from land use change (Zayed 2009). Moreover, isolated populations can also decline or face extinction due the accumulation of deleterious mutations and the inability to adapt to environmental fluctuations (Packer and Owen 2001). A meta-analysis from Canada found Hymenoptera (including bees and wasps) species to be more genetically susceptible to population declines because this order, as a whole, has lower levels of genetic diversity compared to Lepidoptera (the butterflies and moths) species (Packer and Owen 2001). Within the order Hymenoptera, bees exhibited lower levels of genetic diversity compared to other taxa, and bumble bees exhibited by far the lowest level overall. Furthermore, hymenopteran species experience more marked reductions in gene flow as a result of population fragmentation compared to Lepidoptera, making them even more susceptible to declines and extinction when populations become isolated. To ameliorate these issues, land must be managed to increase connectivity between populations of the same species. Conservation practices need to focus on enhancing connectivity of suitable habitats to bring together socially isolated populations

that may go extinct if the gene pools remain isolated, and to maintain diversity in populations that are currently stable (Goulson et al. 2011).

### **Current Legislation Protecting Pollinators in Ontario**

Prior to July 2015, when the regulatory requirements for the sale and use of neonicotinoids came into effect, there was very little legislation specifically protecting pollinators. Much of this existing legislation pertained specifically to the rights and liabilities of keeping honey bees as outlined in the Ontario Bees Act (R.S.O. 1990, Chapter B.6). Additional protection with regards to pesticide exposure for honey bees is specifically outlined within this Act, which could have indirect benefits for other pollinator groups. The protection is outlined as followed, but it is not known how well it is enforced:

“No person shall spray or dust fruit trees during the period within which the trees are in bloom with a mixture containing any poisonous substance injurious to bees unless almost all the blossoms have fallen from the trees.” R.S.O. 1990, c. B.6, s. 18.

In 2007, a paper commissioned by North American Pollinator Protection Campaign (NAPPC) outlining the degree that Canadian legislation protects pollinators concluded that there is inadequate legislation for pollinator conservation (Tang et al. 2007). Managed and wild pollinators fall under provincial, rather than federal, law in Canada. There is no specific legislation in place directly aimed at managed bees (other than honey bees) or wild bees, but the ‘Endangered Species Act’ protects pollinators that are recognized as being ‘at risk’ (S.O. 2007, c. 6). There are currently three species of (bumble) bee, six species of butterflies and two species of moths identified on the CASSARO species at risk list. Through prohibition to damage habitat and the implementation of recovery strategies, other pollinators likely derive indirect benefit from this legal protection. Additional indirect benefits to pollinators may also be received through other general environmental and agricultural protection acts. Revisions to current legislation, or development of new measures, to directly protect wild pollinators in Ontario are desirable. Conserving pollinators in the province, and across Canada, will require us to bringing together the relevant policy makers, scientists, land managers, farmers, and publics (Abrol 2012c). Educating all informed parties and helping policy makers to develop legislation guided by scientific evidence is a necessity (Dicks 2013; Dicks et al. 2013, 2016).

Although there is little legislation directly protecting pollinators, their habitats are often conserved as ‘protected areas’ by the government. Land is protected through Ontario Parks, the branch of the Ministry of Natural Resources that manages 329 provincial parks and 292 conservation reserves. More than 78,000 km<sup>2</sup> are protected through this system, an area approximately 10% of the entire province. The parks also participate in outreach programs to educate the public on the importance of preservation and conservation.

One incentive to urge the development of new pollinator legislations is by determining the economic value of the ecosystem services provided by pollinators in Ontario. Current estimates of crop pollination services provided by managed bees are \$895 million per year (OMAFRA 2014b). Assessing the financial value of the services that these organisms contribute may serve as incentive to preserve biodiversity and natural habitat (Morandin and Winston 2006). The socio-economic values associated with a range of ecosystem services have been calculated for Southern Ontario (Troy and Bagstad 2009). Pollination and dispersal values in this estimate are valued at \$7,608 per hectare, but this value is based



on results from only five studies. However, bees and other pollinators provide additional pollination services that ensure biodiversity of natural flowers and trees, which have implications for soil erosion, water purification, carbon sequestration and habitats for other animals (including human shelter from wood). These results suggest the additional costs of living in a world without pollinators could be extremely high, and calculating this dollar value could underline the need for new conservation policies.

### **Current Lands Protected in Ontario**

Current lands protected in Ontario that may be important habitat for pollinators, mapped using Global Information System (GIS) software, are shown in Figure 20. The shaded areas of the map include federally protected land, conservation reserves, Non-governmental organization (NGO) nature reserves, and the Niagara Escarpment Parks and Open Space System. These lands total about 10% of the province at 106,463.06 km<sup>2</sup>, and include land that, although protected, may not be suitable for pollinators. This map illustrates that there is currently very little land designated for maintaining natural systems. Notably, this protected land is located far away from agricultural- or urban areas, two land-use categories that are found extensively in southern Ontario, in which pollinators habitat is typically most threatened and urgently needed.

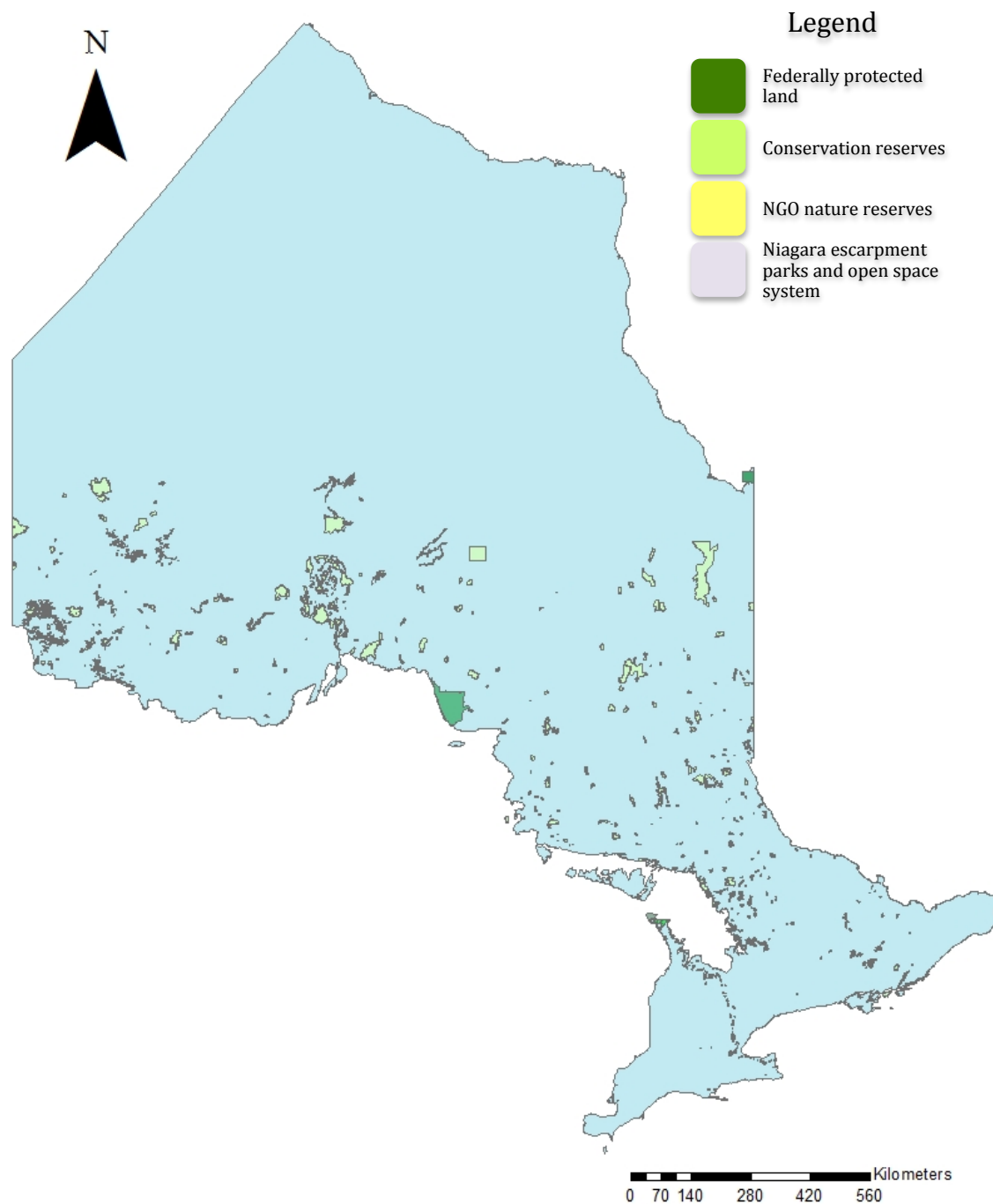
### **Impacts of Conservation Strategies**

Ontario is comprised of a mix of natural and semi-natural land, agricultural land, and urban areas that require a combination of strategies to conserve pollinator species and promote the health of pollinator populations. Evaluations for strategies associated with these land types are reviewed in this section. Although the individual strategies vary, they should all be designed according to the framework outlined in Figure 21.

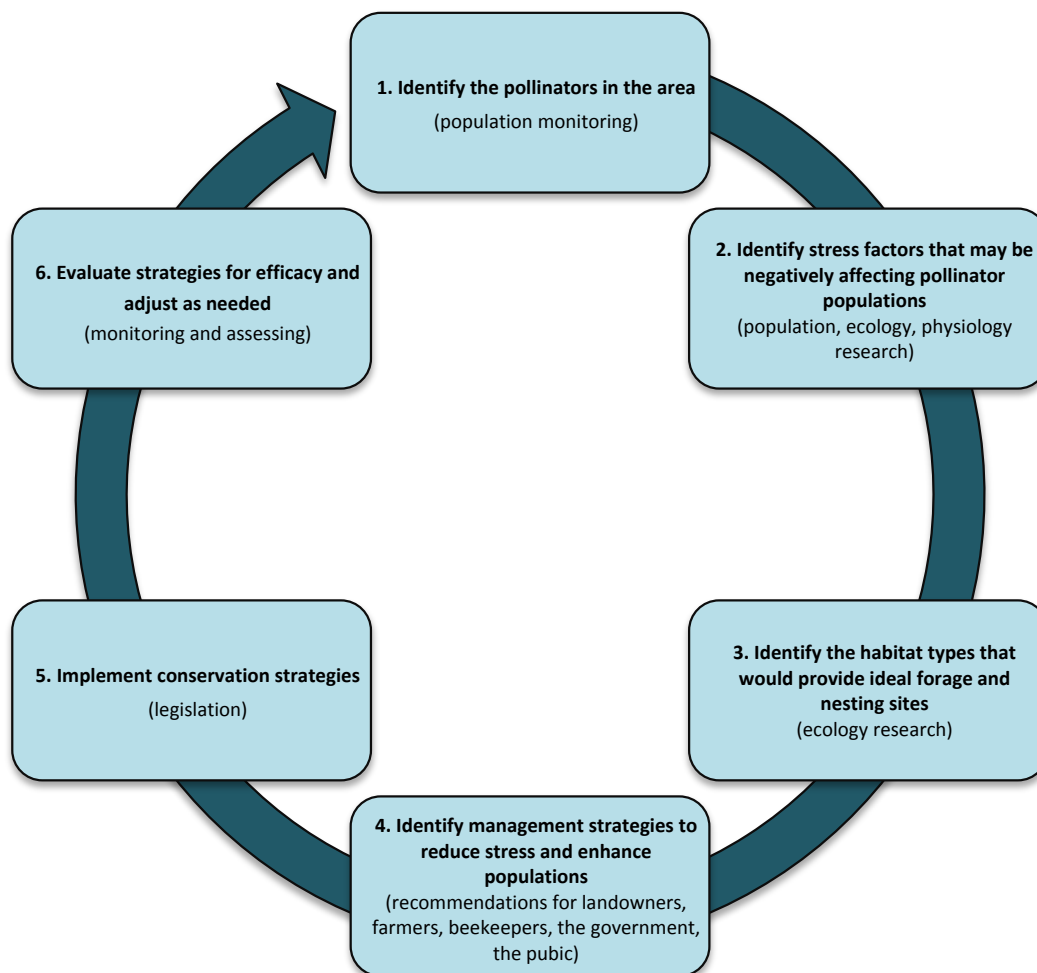
It is critical to implement monitoring programs and to identify particular ecological requirements for individual pollinator species before and after the implementation of conservation strategies, as these will be our best indicators of how populations will respond to any management practices put in place. Overall, we still know very little about the foraging patterns and flower preferences of the majority of pollinator species (Hadley and Betts 2012), though some species (e.g., honey bees and common bumble bee species) are comparatively well studied. Specimen collections that result from these monitoring efforts are important to document diversity measures throughout Ontario and provide historical records with which to refer in the future. In addition to physical collections, organized web databases that are accessible to researchers are necessary to collect and share large-scale data. Such databases, like ‘WebBee’ for bee research, are beginning to be created, but are still not as robust as they could be (Cunha et al. 2001).

The majority of conservation strategies that have been implemented throughout the world are with regards to enhancing and preserving habitat. Habitat planning for bee conservation must take into consideration their foraging preferences as well as their nesting site needs. The majority of wild bees in Ontario are ground nesting and require different soil substrates with the right moisture content and texture. Their foraging is limited in their body size and metabolic demands and, as a result, they may have increased sensitivity to habitat fragmentation (Goulson et al. 2011; Rands and Whitney 2011). Most bees (excluding honey bees) have a maximum foraging range of around 2 km, with some bees closer to 1 km (Zurbuchen et al. 2010b). For this reason, nesting sites must be close to foraging resources and habitat conservation strategies should include both these factors, or accommodate both within foraging range (Greenleaf et al. 2007; Wojcik and Buchmann

2012, Wright et al. 2015). Addressing pollinator habitat as a conservation strategy is most beneficial in areas with intermediate levels of land use (1-20%: Cariveau and Winfree 2015). Pollinator species richness and abundance are the most enhanced in these locations.



**Figure 20.** Map of federal, provincial, municipal, and non-governmental organization protected areas in Ontario.



**Figure 21.** The six steps to develop comprehensive conservation strategies for pollinators.

When adding natural vegetation to any setting, whether it be agricultural or urban, the factor that has the greatest positive influence on pollinators is ensuring there is high flower diversity. Bumble bees prefer to forage in habitats with high flower diversity over high flower density (Jha and Kremen 2013), and there is a positive correlation between the diversity of flowers in agricultural field margins and pollinator abundance and species richness in adjacent crop fields (Saez et al. 2014). Within urban areas, increased flower diversity in gardens and parks is associated with an increase in pollinator visitation (Hennig and Ghazoul 2012).

### Agricultural Strategies

Most agricultural strategies in the USA and Europe have been geared toward creating and preserving pollinator habitat within and surrounding croplands. These pollinator habitats are in the form of hedgerows, wildflower strips, crop-adjacent fields, buffer strips (both within fields to separate crop types and as field margins), and set-aside land. Figure 22 illustrates these different vegetation features. A hedgerow is a line of shrubs, trees, and associated plants that separate agricultural fields and serve as pollinator forage and nest sites, field boundaries, windbreaks, livestock shelter and forage, and soil erosion prevention (Hannon and Sisk 2009). Wildflower strips are planted within croplands to provide additional forage for pollinators and to encourage them to pollinate crops. Crop-adjacent

fields are grasslands or mixed grasslands that support pollinator nesting and forage, ideally free from pesticides. A buffer strip is a long ribbon of vegetation that can be used to protect land against soil erosion and from wind. In agriculture, they can be found within fields or at the edge of a field in the form of a field margin. As a field margin, they delineate the edge of the cropland and can serve as reservoirs for natural enemies and habitat for pollinators. Set-aside land is any land within an agricultural landscape that is taken out of production and restored for wildlife.

Increasing pollinator habitat offers several benefits to agriculture. Wild flowers within and surrounding cropland also serve as habitat for natural enemies that reduce pests and increase overall crop health (Altieri and Nicholls 2004; Baliddawa 1985; Landis et al. 2005). Also, allocating habitat for pollinators enhances crop pollination and significantly improves crop yield (Klein et al. 2012; Mineau and McLaughlin 1996; Morandin et al. 2007; Ockinger and Smith 2007; Scott-Dupree and Winston 1987; Small 1997; Nicholls and Altieri 2013; Saez et al. 2014). Sowing grasses in rotational fallows increases pollinator nesting sites and also enhances soil fertility (Kuussaari et al. 2011). Lastly, set-aside in agricultural fields increases pollinator diversity (Kovács-Hostyánszki et al. 2011).

In addition to adding vegetative habitat, artificial nesting boxes can also increase pollinator populations in agricultural settings. Trap nests (bee hotels) can be installed near orchards to attract cavity-nesting bees. A study in Nova Scotia installed trap nests in wild habitats, apple orchards with no pesticides or mowing practices, and apple orchards with pesticides and mowing practices and found that bees inhabited trap nests in all locations (Sheffield et al. 2008b). The authors found the trap nests increased and maintained populations throughout subsequent years and conclude their installments may be a beneficial management practice for orchard farmers. Nesting sites can be a limiting factor for pollinators, especially in agricultural lands that practice mowing and tilling, and providing suitable nesting sites can improve bee populations even when other management practices known to be detrimental to pollinators are being used.

### Summary of Evidence

The majority of scientific research investigating conservation strategies for pollinators is in the form of studies that evaluate habitat on agricultural land. While there are no empirical peer-reviewed studies assessing the impacts of adding pollinator habitat to agricultural land in Ontario or Canada, there is well established evidence from the USA and Europe that added habitat within and surrounding agricultural land increases pollinator abundance, diversity, and reproduction (e.g., Haaland et al. 2011; Nicholls and Altieri 2013). Maintaining pollinator habitat not only provides forage, but also nesting sites for bees (Buri et al. 2014; Lye et al. 2009). Although allowing natural vegetation to grow is beneficial on its own (Croxtton et al. 2002; Kells et al. 2001), the evidence shows pollinators are most successful in vegetation that is planted with native perennial wildflowers (Carvell et al. 2007; Morandin and Kremen 2013a; Potts et al. 2009; Redpath-Downing et al. 2013), especially those that are high in nectar and pollen (Blake et al. 2011a; Goulson et al. 2011). These planted habitats also support a greater number of rare bee species (Hannon and Sisk 2009) than natural habitats. There is also well established evidence that adding pollinator habitat benefits crop production. Habitat surrounding orchards increases pollination of fruit trees (Watson et al. 2011), and habitat surrounding crop lands also increases pollination levels (Le Feon et al. 2010; Morandin et al. 2007; Williams 1986) and crop yield (Blaauw and Isaacs 2014b; Kremen et al. 2004; Morandin and Winston 2006; Ricketts et al. 2004).

There is established but incomplete evidence that wild pollinators provide the best services in small crop fields compared to large crop fields. A large scale study in Ontario, as well as a European study, found increased biodiversity of several organisms including pollinators in smaller scale farmlands (Belfrage et al. 2005; Fahrig et al. 2015). There is conflicting evidence as to whether increased crop diversity benefits pollinators; responses depend on the types of crops as well as the pollinator species in question. Similarly, there is variation in how pollinators respond to organic farming depending on species and landscape features. Studies from Canada and Europe found organic farming increases bee, butterfly, and wasp populations (Feber et al. 1997; Holzschuh et al. 2010; Morandin and Winston 2005), but other studies from Europe found organic farming did not make any difference compared to conventional farming (Ekroos et al. 2008; Holland et al. 2015). There is no evidence from Ontario or Canada on the efficacy of integrated pest management programs to protect pollinators from pesticides. Well established evidence from Europe, however, shows that integrated pest management programs are effective at lowering pest levels and reducing the dependancy on pesticides (Anderson 2010; Lewis et al. 1997). Lastly, well established evidence from Europe, in the form of individual studies as well as meta-analyses, find that agri-environment schemes implemented by the government are effective in increasing pollinator diversity and abundance in agriculturalized lands when implemented appropriately (e.g., Batáry et al. 2011), but the degree of a scheme's success depends on many factors.

### **Adding and Maintaining Pollinator Habitat**

Adding pollinator habitat to agricultural fields can be achieved in a variety of ways, including adding wildflowers and nesting resources within and surrounding cropland. New recommendations for agri-environment schemes in Europe suggest a combination of these options are required to enhance pollinator populations. Planting 1-4 hectares of flowering forage and providing 0.5-2 hectares of nesting resources per 100 hectares of farmland is enough to provide six common pollinator species (solitary and bumbele bees) with nests to reproduce and food to feed their larvae (Dicks et al. 2015). Details vary depending on the type of farm, the species of seeds planted, and the pollinators present. This section reviews suggested strategies for adding and maintaining pollinator habitat in agricultural settings. These evidence-based recommendations have been incorporated into the UK Wild Pollinator and Farm Wildlife Package (WPFWP: Natural England 2015), an agri-environment scheme that pays landowners to create and manage habitat for insect pollinators. Generating estimates of the diversity and abundance of floral and nesting resources needed to support pollinators in the landscape is likely to be more challenging in Ontario due to severe knowledge gaps in the ecological requirements of pollinator species of concern.

### **Planting and Maintaining Wildflowers Within Cropland**

The simplest method to maintaining flowers within a cropland is to allow some to grow wild. Agricultural fields with management practices that reduce within-crop flowers (such as using herbicides) typically have lower bee diversity (Mand et al. 2002; Osborne et al. 1991). Studies in the UK (Smith 1969) and the USA (Altieri 1977; Root 1973) demonstrate the benefit of maintaining some wildflowers in cropland as fields that contain some flowers experienced fewer outbreaks of pest insects, and have more resident natural enemies, compared to fields without wild flowers. In places where farmers choose to maintain some wildflowers within or around their crops, competition thresholds should be calculated to determine the floral abundance and diversity a field can support before it causes

competition for water, nutrients, and sunlight with crops and associated yields effects (Oliver 1988). Alternatively, wildflowers that act as weeds can be removed during the critical crop blooming period but allowed to grow before and after this period.



**Figure 22.** Different vegetative features that can be added to agricultural land to improve pollinator populations, in the form of a hedgerow (a), wildflower strip (b), buffer strip in the form of a field margin (c), crop-adjacent land (d), and set-aside land (e). Photos are from Nicholls and Altieri (2013); Vaughan et al. (2007); and USDA (2009).

More research is needed to identify the most beneficial flower species to encourage pollinators (Nicholls and Altieri 2013). Some flower species do not serve as good habitat and forage for pollinators and natural enemies, whereas others do. The largest study to examine suitable flowers was conducted in Switzerland by Nentwig (1998) who found there was high variation in natural enemies, herbivores, parasitoids and pollinators on different species and identified the most and least attractive for cropland in the region of Berne. He found the most attractive plants were poppy and tansy, supporting over 500 arthropods. In cases where farmers find it too difficult to maintain any wild flowers within their farm fields because it interferes with normal farming practices, Nicholls and Altieri



(2013) recommend that they plant hedgerows that contain flowering plants. These hedgerows should also supply nesting sites for pollinators in the form of open soil and dry logs and branches.

Planting rows of wild flowers, referred to as ‘wildflower strips’, within crop fields can serve to attract pollinators. Overall these strips have resulted in increases of pollinator species abundance and diversity (Haaland et al. 2011; Scheper et al. 2016). For example, Nicholls and Altieri (2013) planted strips of alyssum on a farm in California and found they attracted syrphid flies. Some, but not all, studies find wildflower strips also increase the number of natural enemies (e.g., Tschumi et al. 2014; Hausanmmann 1996). The efficacy of these flower strips likely depends on the flower species planted and the cropping system (Haaland et al. 2011).

Assessing the attractiveness of flower species, specific varieties and seed mixtures for pollinators is an important aspect of choosing appropriate plantings within cropland (Carreck and Williams 2002; Pontin et al. 2006; Olwell and Riibe 2016; Redpath et al. 2010; Russo et al. 2013; Vaudo et al. 2014). The results of this type of work have led to development of floral mixtures including ‘pollen and nectar’ flowers and ‘wildflowers’ for agro-environment schemes in the UK (Carvell et al. 2007). The diversity of bees is highest when there are fifteen different flower species present in a landscape (Nicholls and Altieri 2013). Actively planting wildflowers has also been shown to be more beneficial to pollinators compared to natural fields. A study in California found that native bee and syrphid fly abundance and diversity is significantly higher in cropland edges planted with native perennials compared to cropland edges that were unmanaged and left to grow wild (Morandin and Kremen 2013b). These planted edges contained more rare species and led to increased crop pollination than wild edges. Similar effects are also seen with planted hedgerows. Habitat restoration within farmland may be further enhanced if hedgerows and edges are planted and maintained instead of just being left to develop on their own. Planted hedgerows contain more rare bees than wild hedgerows that develop their own flowers (Hannon and Sisk 2009). However, wild field margins and hedgerows are still more beneficial to bees than the absence of any natural habitat (Croxtton et al. 2002; Kells et al. 2001).

### **Maintaining Natural and Semi-Natural Land Adjacent to Cropland**

The presence of ideal habitat surrounding crop fields is beneficial for pollinators and it also increases crop pollination. In general, croplands with greater proportions of natural surrounding land have higher pollinator species richness and abundance (Kremen et al. 2002, 2004; Steffan-Dewenter et al. 2002, 2003; Williams and Kremen 2007). Several studies have examined the impact of adjacent natural land on orchard pollination. One study in British Columbia compared wild bee capture rates in orchards adjacent to and far from natural land (Scott-Dupree and Winston 1987). Significantly more wild bees were captured in orchards adjacent to natural vegetation. Similar orchard studies in the USA have found the same relationship (Klein et al. 2012). In land far from natural vegetation, planting a flower strip within orchards increased the abundance of wild bees present (Klein et al. 2012). Another study in British Columbia found bees important for orchard pollination (*Bombus* and *Osmia*) are found in greater abundances in vegetation surrounding orchards (Scott-Dupree and Winston 1987). These authors recommend planting perennials near orchards that bloom before and after orchard blossoms to encourage the establishment of wild pollinator populations for orchard pollination. Apple orchards with a forested area within 1000 m had a significant positive impact on wild bee species diversity (Watson et al.

2011). The greater the proportion of forest within 1000 m, the higher the number of wild bee species found pollinating orchards. The proportion of pastureland surrounding orchards was also associated with increased wild bee species richness, whilst the proportion of land used as roads and nonagricultural developed lands in the form of houses or lawns was a negative predictor of the number of wild bee species pollinating the orchards.

The same impact on pollinators is seen in crop studies. In the US, wild bee visitation to cucumber increased with the proportion of semi-natural land beside the field (Smith et al. 2013). The highest visitation was seen when natural land was within 250 m of the farmland. Canola fields surrounded by semi-natural pastureland within 800 m of cropland contained significantly more bumble bees than fields surrounded by more tilled farmland (Morandin et al. 2007). The same authors also determined maximum seed production and crop yield is achieved when 30% of farmland is converted to natural habitat within 750 m of the field edge (Morandin and Winston 2006). Studies in the USA on watermelon (Kremen et al. 2004), and in South America on coffee (Ricketts et al. 2004), also found crop yield to increase when uncultivated, natural land is nearby. Lastly, research in Europe has found the closer croplands were to natural, uncultivated land, the more bumble bees were found visiting and pollinating crop flowers (Le Feon et al. 2010; Williams 1986). Planting perennial wildflowers adjacent to croplands also increases pollination and crop yield in blueberries in Michigan (Blaauw and Isaacs 2014a, 2014b). Taken together, these studies show that having natural land for nesting and foraging bees near cropland helps to increase bee populations pollinating crops. Bees have been shown to forage on fields adjacent to cropland before crops have bloomed (Hannon and Sisk 2009), forage on crop plants during their blooming period, and then move again to adjacent fields that bloom afterward (Mandelik et al. 2012).

The type of natural habitat adjacent to cropland influences pollinator abundance. Studies from Europe show that wild bee and butterfly species diversity and abundance is greatest in crop adjacent land that contains flowering plants (e.g., clover, thistle, daisy) compared to fields with grassy margins (Backman and Tiainen 2002; Potts et al. 2009; Redpath-Downing et al. 2013), receives plenty of sunlight versus shady areas (Sydenham et al. 2014), and receives no fertilization and reduced mowing and grazing (Potts et al. 2009).

Private gardens in the backyards of houses located near agriculture lands also have a positive effect on bee populations and crop pollination. Bee species richness, bee abundance, and plant seed set were increased when gardens were near crop fields in Sweden (Samnegard et al. 2011). However, this effect was strongest when gardens were less than 15 m from a farm field and were least when they were more than 140 m away. The proximity required for this effect makes it unlikely to rely on this strategy alone for providing pollinator habitat.

Grasslands near agricultural fields provide good nesting sites for wild bees. Mowing regimes to maintain nesting sites for bees, in combination with wildflower strips that provide good forage for bees, optimize overall habitat in intensive agricultural land (Buri et al. 2014). The largest field scale mowing study in Switzerland compared mowing regimes to see which was most beneficial for bees (Buri et al. 2014). The first regime was leaving part of a meadow unmowed to provide some permanent habitat for bees. The second regime was delaying mowing the entire meadow by one month to provide more habitat for bees during their most active nesting period. The authors found leaving 10-20% of a meadow permanently unmowed is most beneficial to species abundance. Species richness did not differ between the two regimes.



### **Promoting Pollinator-Friendly Field Margins**

Overall, bumble bees prefer field margins that are managed (i.e., participating in agri-environment schemes) over those that are unmanaged on farmlands (Lye et al. 2009). Similar to managing surrounding lands, pollinators prefer field margins with flowers compared to only grass. Butterfly species richness increased in grassy buffer strips enhanced with wildflowers compared to grass alone (Blake et al. 2011b), species richness of common and rare bees is significantly higher in margins with wildflowers compared to grass alone (Pywell et al. 2012), and bumble bee queens prefer to nest in grassy field margins with some establishment of early-season flowering plants (Lye et al. 2009). An added benefit is that the vegetation community itself is more stable when it is incorporated with a diverse assemblage of wildflowers compared to grasses in which competitive species dominate (Pywell et al. 2011). A recent UK study compared the efficacy of planted wildflower margins along crop field edges and found these strips brought significant improvements in bumble bee reproduction (measured by the number of queens and males) at both local and landscape levels (Carvell et al. 2015). The effects were greatest for planted strips larger than one hectare, and smallest in strips smaller than 0.25 hectares. Larger strips are thought to facilitate dispersal of males and queens to surrounding land.

Considerable effort is underway to determine the most beneficial flowers to plant in field margins. To date, studies show that bees prefer ‘pollen and nectar’ mixes from the range of wildflower mixes available under agro-environmental schemes in Europe (Pywell et al. 2006, Carvell et al. 2007). Carvell and colleagues (2007) tested three field margin management schemes over three years to determine which were most beneficial to bumble bee populations. One treatment was a margin planted with a ‘high pollen and nectar’ flower mix, one was a margin planted with a wildflower mix, and one was a margin that was left natural to grow its own flowers. The margins planted with a ‘high pollen and nectar’ mix produced the highest total number of flowers, followed by the wildflower mix and then the naturally regenerated margins. Flower species in all margins changed over the three years due to succession. The greatest bumble bee species richness of all years was seen in the ‘high nectar and pollen’ flower mix margins, but by the third year there were as many bees in the ‘wild flower’ mix margins. There was also a positive correlation between the number of flowers in a margin and the number of bees present. Carvell et al. (2007) recommend that seeds should be planted in margins as opposed to allowing margins to regenerate and develop plants naturally to attract pollinators with sufficient forage sources.

Further research into seeds could lead to creating a mix that allows flowers to bloom in succession throughout the season. Resowing may be needed every few years to rebalance the species’ proportions and prevent one (or a few) from becoming dominant. Expanding the agri-environment schemes to the landscape level may also be beneficial. Instead of all farms planting the same mix, heterogeneity can be re-established by planting different mixtures both within and across farms. Models indicate that the width of field margins can also influence bee populations. Wider margins are more beneficial for bees (both honey bees and solitary bees) than narrow margins in that they provide more available forage (Rands and Whitney 2011), but the ideal size remains to be determined.

### Choosing Small Crop Fields Over Large Crop Fields

How cropland is arranged within the landscape can have significant conservation benefits. A study conducted throughout Eastern Ontario examined overall species diversity in different sized crop fields (Fahrig et al. 2015). Researchers measured the number of species of birds, butterflies, bees, flies, carabids, spiders, and plants at 93 sample sites in two years. The most significant finding from the study was that smaller fields were associated with increased biodiversity. This increase in biodiversity was found even when the amount of natural land within the study areas were directly comparable. A similar study in Sweden found farms that were less than 52 hectares in size contained twice as many butterflies and five times as many bees as farms that were larger than 135 hectares (Belfrage et al. 2005). Figure 23 demonstrates how the scale of cropping fields affect pollinators. Landscape A has smaller field sizes compared to Landscape B, but both areas contain the same amount of natural habitat. These smaller scale croplands allow pollinators easier access to field boundary habitats. This is important considering the comparatively short flight ranges of many bee species. Taken together, these studies suggest that plentiful and well managed field boundaries separating crop fields provide better and more accessible habitat than scattered forest patches (as seen in Landscape B), and a useful conservation priority is promotion of smaller crop fields.

There is conflicting evidence whether having many different kinds of crops within a field increases pollinator species biodiversity. Fahrig et al. (2015) found in fields that are 1 km<sup>2</sup>, multiple crop types have no effect on pollinator populations compared to monocultures. Another study examining the agri-environment scheme in Iowa to increase crop diversity found multiple crops in one area was beneficial for bird populations (Lindsay et al. 2013). This emphasizes that species respond differently to the same conservation measures.



**Figure 23.** Pollinator biodiversity is higher in landscapes with smaller (Landscape A) compared to larger field size (Landscape B). Importantly, both landscapes are 1 km<sup>2</sup> (pollinator scale) and contain the same amount of natural area (modified from Fahrig et al. 2015).

### **Organic Farming and Pesticide Restrictions**

Organic farming is associated with higher levels of biodiversity compared to conventional farming, but studies show a lot of variation depending on the species investigated and the landscape features of the farm (Bengtsson et al. 2005; Hole et al. 2005). In particular, organic farms can be more beneficial to pollinators because of the absence of pesticides, the greater diversity of floral species for habitat and forage, the size of farms (organic fields tend to be smaller) and usually have more incorporated natural habitat than conventional farms (Nicholls and Altieri 2013). Morandin and Winston (2005) studied canola agriculture in Alberta and found bee abundance is highest in organic fields, followed by conventional fields, and lowest in fields planted with genetically modified (herbicide resistant) canola. The trend was reversed when taking into account pollination deficits. That is, genetically modified fields experienced the highest pollination deficits and organic fields experienced the lowest. Herbicide resistant canola fields have high levels of pesticide used and the lowest floral diversity (due to herbicide application) to serve as bee habitat and forage. Studies in Europe also record more pollinating butterflies (Feber et al. 1997) and increased species richness of bees and wasps (Holzschuh et al. 2010) on organic farmland compared to conventional farmland. There were no reported differences in the abundance of pest species between the two farms. However, some UK studies have found organic farming did not improve pollinator populations (Ekroos et al. 2008; Holland et al. 2015).

In cases where it is unsustainable to farm organically, reducing pesticide use can have significant benefits for pollinators. Using herbicides significantly reduces pollinator populations by removing nesting habitat and food sources. Many crops have a short blooming time and bees with flight periods that extend beyond this blooming time may find themselves without food. A study in the UK monitored butterfly populations for four years and confirmed that agricultural headlands sprayed with less herbicide under a conservation regime contain significantly more butterflies than fully herbicide-treated headlands, and that these populations were increasing (Dover et al. 1990). Reducing insecticides is also beneficial for pollinators, and restrictions are beginning to be implemented around the world. In 2013, the European Commission was the first to initiate the restriction of three neonicotinoids on crops attractive for bees for a period of at least two years until further research was conducted on their environmental safety (Woteki 2013). On July 1, 2015 Ontario launched the first North American restriction on neonicotinoid seed treatments in agriculture. Although it will take time to evaluate the efficacy of the restriction in Ontario, results from Europe should provide some insight as to whether the insecticide restrictions led to a reversal in bee declines and a recovery in pollinators, as predicted.

If reducing or avoiding pesticides is not an option, Atkins et al. (1978) recommends the following strategies to reduce pesticide exposure to bees:

- Apply pesticides at night when bees are inside their hives and nests. Direct exposure to honey bees is reduced and the pesticide is allowed to dissipate for longer.
- Avoid application during bloom. Apply several days before the crops have bloomed or after they have finished blooming.
- Physically move managed bees out of fields during the spray period (about one mile). Return them to the fields after a few days.
- Opt for pesticides with spray applications, as these are generally safer to bees than pesticides in dust applications.
- When possible, opt for lower doses of pesticides as concentration and amount can have different effects on bee toxicity.

### **Integrated Pest Management to Protect Crops**

Integrated pest management practices and crop rotations using alternative crops has been shown to improve pest control, reduce pesticide dependency, and improve soil nutrient cycling (Anderson 2009, 2010). A fifteen-year study in The Netherlands examined the efficiency of integrated pest management practices and found that the reliance on insecticides and fungicides to control pests and pathogens decreased by 90% (Lewis et al. 1997). These studies found the following practices to be successful integrated pest management strategies:

- Replacing artificial fertilizers with organic manure
- Enriching the natural enemy fauna by providing them with more habitat
- Planting pest- and disease-resistant crops
- Reducing nitrogen fertilization
- Reducing pesticide use
- Using at least four different crops in rotations

Integrated pest management practices need to take a more active approach on how an ecosystem functions and the role of natural enemies. The focus needs to be toward increasing populations of native natural enemies to target crop pests through managing their habitat (Lewis et al. 1997). It is important to have natural enemy populations at effective levels by the time crops begin to grow. Sowing earlier blooming forage and habitat plants can help achieve populations to peak for the crop growing period (Lewis et al. 1997).

### **Agri-Environment Schemes**

Agri-environment schemes are programs that help and encourage farmers to manage their land in a more environmentally sustainable and responsible manner. Farmers are paid, often by the government or a non-for-profit organization, to manage their land in ways that benefit species, the ecosystem services they provide and their habitats. These practices include altering management to reduce soil erosion, runoff, and agrochemical drift, and establish or restore habitat and food for birds, insects, and mammals. Farmers sign a legal contract for a fixed number of years and receive payment for the environmental benefits they are providing (e.g., DEFRA 2005, 2013). The following are a modified list of the practices implemented through these schemes that are beneficial to pollinators, adapted from Batáry et al. (2015) and Sepp et al. (2004):

- Establish/enhance field margins and hedgerows
- Maintain/enhance semi-natural and natural elements
- Decrease field size and extent of croplands
- Practice crop rotation
- Restrict pesticides or practice organic farming
- Alternative mowing regimes
- Clear shrubs
- Take areas of land out of production (including marginal land)
- Reduce fertilizer
- Reduce stocking rates of grazing animals on fields

The European Union (EU) is the largest proponent of agri-environment schemes in the world and has them in place since 1985 (Batáry et al. 2015). The EU has conservation funding for these schemes, and since 1992 it is mandatory for all member states to participate in these programs according to the EU Rural Development Regulation (Batáry et al. 2015), with each member state responsible for developing its own schemes. But while it

is compulsory for these countries to have agri-environment schemes in place, it is voluntary for the landowners to enroll in them. As of 2004, only about 20% of farmland operating in the EU was enrolled in agri-environment schemes (Sepp et al. 2004). Because these schemes have been in use for 30 years, it is now possible to evaluate their efficacy. Overall, research demonstrates these schemes are effective in enhancing biodiversity and preventing the further loss of biodiversity when they are properly implemented (Batáry et al. 2015; Carvalheiro et al. 2013). They have also been shown to improve pollinator species richness and abundance (Albrecht et al. 2007; Knop et al. 2006; Marshall et al. 2006; Pywell et al. 2006).

A meta-analysis conducted by Batáry and colleagues (2011) examined 109 studies comparing plant and animal species richness and diversity between agri-environment scheme lands compared to control sites and found all studies reported positive results. A later meta-analysis by the same authors found that agri-environment schemes targeted at the edges and surroundings of crop fields (such as establishing and improving hedgerows, field margins, and surrounding land) were significantly more effective at restoring species richness compared to schemes targeted within the croplands themselves (such as altering the use of pesticides and mowing; Batáry et al. 2015). However, other large-scale evaluations suggest that most agri-environment scheme studies are inadequately designed to reliably measure their effectiveness (Kleijn et al. 2001; Kleijn and Sutherland 2003), and although they improve overall diversity and abundance, they do not offer much benefit to rare species (European Court of Auditors 2011; Kleijn et al. 2015).

The degree of a scheme's success depends on a number of factors (Batáry et al. 2010; Morris et al. 2011; Potts et al. 2011). The outcome depends on where the habitat is implemented on the land (Kleijn et al. 2006; Kohler et al. 2007; Lye et al. 2009), how it is incorporated into the land (e.g., patch size, connectivity, heterogeneity; Carvell et al. 2011; Heard et al. 2008, Rundlöf et al. 2008), the functional group/genus/species being targeted (Kohler et al. 2007), and how the land is being manipulated to become pollinator habitat (Kleijn et al. 2006; Kohler et al. 2007). For example, agri-environment schemes are more effective in increasing species richness in simple compared to complex agricultural crop landscapes (Batáry et al. 2011). It is thought that complex landscapes with high levels of heterogeneity and semi-natural vegetation already encourage high pollinator populations, and are therefore not as impacted by schemes than simple homogenous landscapes with low pollinator populations. Furthermore, not all species respond the same to agri-environment schemes (Sjodin et al. 2008), and therefore they are most effective when targeted toward the needs of specific species or functional groups (Kleijn and Sutherland 2003; Wood et al. 2015). For instance, Sepp et al. (2004) monitored bumble bees in areas where these schemes were implicated and found that bumble bee distribution depended on certain landscape features, namely the acetone length between the farmland and the forest edge, and the amount of land covered in forests and wetlands. Also, bumble bee species richness and abundance was lower in farmlands that were intensively farmed (>65% of land) versus those that were less intensely farmed (<45% of land).

In spite of mandatory national enrollment to agri-environmental schemes in the EU, these programs are not always widely adopted or properly implemented. In 2011, only 0.05% of land in England contained the recommended 'pollen and nectar' wildflower mix for agri-environment schemes (Blake et al. 2011a; Goulson et al. 2011). Holland and colleagues (2015) surveyed scheme efficacy for pollinators in England and found that the amount of land incorporated in these schemes for pollinators is still insufficient. Pollinator populations

on farmland with improperly implemented agri-environment schemes are no better off than those on farms with no schemes at all (Lye et al. 2009). Educating landowners on the proper way to create and manage pollinator habitat, as well as later visiting these lands to ensure the schemes are properly implemented, is important. Monitoring and evaluating the schemes for their efficacy after implementation is urgently needed (Kleijn and Sutherland 2003; Pywell et al. 2012). A special report by the European Union found administrative authorities provide feedback to only 2% of landowners participating in an AES contract (European Court of Auditors 2011). The design of a good agri-environment schemes is not in itself enough to support biodiversity; it is necessary to engage farmers and land owners to use them. The agri-environment schemes must be user-friendly and consider the landowner's attitudes and constraints (de Snoo et al. 2013).

In addition to improving enrollment, enhancing agri-environment schemes may also be needed. In the UK, about 30,000 hectares of land is incorporated into perennial grasslands according to agri-environment schemes; however, these grasslands would be more beneficial for pollinators like bumble bees and butterflies if wildflowers were incorporated (Blake et al. 2011a; Potts et al. 2009; Pywell et al. 2011). This would ensure both food and nesting resources are available. As pollinator biodiversity continues to decline in Europe, improvements to agri-environment scheme policies are needed. Sadly, reforms of these policies show they are not becoming more effective over time (Pe'er et al. 2014).

### **Suggestions**

Adding and maintaining pollinator habitat in agricultural areas is beneficial for pollinators. Leaving some wildflowers to remain in cropland, planting flower strips within farm fields, and enhancing hedgerows and margins with wildflowers have been shown to increase pollinator abundance and species richness. Pollinators thrive on lands enhanced with native perennials more so than on natural land. Field margins are most beneficial if wildflowers are added to grassy margins to provide both nesting and forage resources for pollinators. Bees exhibit a preference for 'high pollen and nectar' flower mixes. Natural and semi-natural habitat adjacent to agricultural land increases pollinator diversity and abundance. It can also significantly increase pollination success and crop yield. Ideally, natural land should be located within 250-1000m of agricultural land. Land with flowering perennials, receiving plenty of sunlight, receiving little fertilizer and infrequently mowed is preferred by many pollinator species.

Pollinators prefer smaller over larger crop fields. Plentiful field boundaries provide easily accessible nesting and non-crop forage sites. These boundaries are better for pollinators than scattered forests within farmland. Overall, organic farm management is more beneficial to pollinators than conventional farming, but there is variation due to the crop and pollinator species present and landscape features of the farm. Reducing herbicide and insecticide use is generally associated with increased pollinator populations. Bees can be protected (to a degree) from pesticide exposure if certain management practices are used during application times (e.g. avoiding spraying during the crop flowering period). Integrated pest management can support increases the populations of beneficial insects (including both pollinators and natural enemies) through habitat preservation and enhancement. Other strategies that reduce pests include using organic manure, planting pest-resistant crops, and using a minimum of four different crops in rotations.

Evidence from agri-environment schemes in Europe indicates that they are effective in increasing pollinator abundance and diversity. Ontario should consider similar programs to

maximize pollinator conservation. A first step to this would be to estimate the diversity and abundance of floral and nesting resources needed to support pollinators in Ontario landscapes (using a process like Dicks et al. 2015). These estimates could then be used by the province to inform programs for establishing and maintaining suitable habitat. Agri-environment schemes are most effective if they are based on scientific evidence and are evaluated for their efficacy after they have been implemented.

### Urban Strategies

Habitat loss due to urbanization is a significant threat for bees in Ontario, however, allocating nesting and foraging resources in a city can help ameliorate this stress and maintain their populations (see page 40). The community of pollinators found in urban areas is often unique compared to those found in agricultural areas and natural areas, and may therefore require specific conservation strategies (Sattler et al. 2011).

### **Summary of Evidence**

There is well established evidence from Canada and Europe that adding pollinator habitat to urban landscapes increases their abundance and diversity. Landowners who enhance their backyards with wildflowers contribute to this result (Gunnarsson and Federsel 2014), so promoting bee-friendly gardens to the general public is worthwhile. Even small gardens within cities can provide ‘stepping stone’ habitats to increase connectivity to larger habitats, and high flower diversity contributes most to pollinator increases (Hennig and Ghazoul 2012). There is inconsistent evidence from studies in New York City and one study in Europe that urban greening increases species richness (Hennig and Ghazoul 2012; Matteson et al. 2008; Matteson and Langellotto 2011). This may be due to the different community of pollinators that is already found in cities compared to natural areas to begin with. Studies also show pollinators do not discriminate between native and ornamental flowers (Harrison and Winfree 2015; Jha et al. 2013), but it is encouraged that native flowers are planted whenever possible.

### **Urban Green Space**

Adding flowers to urban landscapes are successful in attracting bees (Wojcik and McBride 2012), but different types of urban green space vary in their benefit to pollinators. Tommasi and colleagues (2004) examined bee diversity and abundance in four different types of urban setting in Vancouver, British Columbia. The settings included traditional urban backyards with mowed lawns and few native plant species, ‘naturescape’ backyards with a variety of native plants and infrequently mowed areas, botanical and community gardens, and wild areas along power lines and road edges. The authors found botanical and community gardens had the highest honey bee and wild bee abundance and traditional urban backyards had the lowest. Similar wild bee abundance was reported between botanical/community gardens and naturescape backyards. Researchers in Sweden found a positive correlation between bumble bee abundance and flowering frequency in urban gardens, and even ornamental flowerbeds contributed to high species diversity (Gunnarsson and Federsel 2014). These studies show that bee abundance can be improved in urban areas by encouraging landowners to plant specific flowers in their backyards and for cities to convert portions of land into botanical or community gardens.

Although urban conservation schemes promote increased abundance, there is inconsistent evidence to show they increase species richness. Hennig and Ghazoul (2012) investigated how flower density, flower abundance, area of green space, and density of green space edge

influences the number of pollinator species. They found flower diversity significantly increased the number of bee species, bee flower visits, and syrphid flower visits. Floral abundance also significantly increased bee species richness and bee flower visits. The size of the green space also had a positive affect on the number of bees present. The authors conclude that even small gardens within urban areas are important for pollinators and may increase connectivity by serving as short ‘stepping stone’ sites on the way to larger foraging areas. However, a study that examined urban gardens in New York did not find any relationship between the addition of native plants to gardens and beneficial insect species richness (natural enemies and pollinators: Matteson and Langellotto 2011). Furthermore, butterflies and megachilid bees preferred exotic ornamental flowers to native flowers when both were present in gardens. The authors do note, however, that the amount of native flowers added to gardens were few in relation to the number of flowers already present, and they conclude that benefits in species richness may be attained when flowers are added to initially small gardens or to gardens with very low species abundance. In urban areas, non-native bees tend to exist significantly more than wild species and bees do not show a preference for native- versus exotic plants (Harrison and Winfree 2015; Jha et al. 2013).

The community of pollinators in urban areas is different from those in natural areas, and this may be the reason that species richness does not always increase like abundance from urban green space. Compared to bee surveys from natural areas within 150 km of New York City, bee species richness is reduced in urban gardens and the bees found in these gardens are most often cavity nesters and exotic species (Matteson et al. 2008). Although species richness is not as high as outside urban areas, gardens can provide refuges for bees within cities. Another survey of bees in a suburban landscape near New York City showed suburbs have the potential to be habitats for many bee species and harboured similar species richness to a natural research preserve nearby (Fetridge et al. 2008). In urban landscapes, enhancing flowers at the local scale (i.e. community gardens, backyards, city parks) is most impactful to pollinator populations compared to enhancing habitat at the large scale (Williams and Winfree 2013).

Lawn care in urban and suburban areas can also influence pollinators. In Ontario, it is illegal to spray herbicides on your lawn for cosmetic purposes (Government of Ontario 2009). Pollinators use dandelions and white clover as a food source and are found in abundant numbers in urban and suburban lawns that have not been very well maintained (Larson et al. 2014).

### **Bee Hotels**

Nesting sites can be a limited resource for wild bees (Stubbs et al. 1997), and studies in Ontario have examined the use of trap nests ‘i.e., bee hotels’ as alternative nest sites. In theory, trap nests should increase bee populations and have historically been used in agricultural lands to increase pollination (Bosch 1994; Hallett 2001; Stubbs et al. 1997). They have only recently begun being implemented into urban areas (Gaston et al. 2005). The installation of these hotels is increasing in popularity with the assumption that they are helping increase native bee populations and have become a common method of citizen science (MacIvor and Packer 2015). In reality, bee hotels are still in the early phases of development and have several drawbacks associated with them. For example, MacIvor and Packer (2015) surveyed 600 bee hotels in Toronto and found that these hotels harboured more wasps and introduced bees than native bees, and native bees experienced more parasitism than the introduced bee species.



Constructing bee hotels with different nest diameters, pathogen- and mould-resistant construction materials, lower elevations above ground, and facing different directions may enhance attracting native bees (MacIvor, pers. comm.). Increasing shade to bee hotels has been shown to increase wild bee nesting (Taki et al. 2004). These hotels hold promise as a conservation tool, but require further development before being implicated.

The most positive outcome from these studies of bee hotels is showing that citizen science can be an effective tool for pollinator conservation. A study from the USA on recruited 655 participants to construct bee hotels and monitor them in a variety of ecosystems (Graham et al. 2014). This study shows the public is interested and willing to help pollinators and contribute to monitoring endeavors. Simple projects like this one, called the Native Buzz project, are far reaching and could be an efficient way to monitor some pollinator species in urban environments.

### Post-Industrial Sites

Abandoned industrial sites (referred to as brownfield sites) experience succession that may serve as good habitat for wildlife. Research into their use as pollinator habitat in urban areas was outlined by Macadam and Bairner (2012), but more research is warranted. The article outlines two brownfield site projects. ‘All The Buzz in the Thames Gateway’ in southern England was a project that analyzed the biodiversity in 1,000 restored brownfield sites. The analysis uncovered that one third of all brownfield sites supported high levels of biodiversity, with some sites being important remaining sites for the declining bees *Bombus humilis* and *Bombus sylvarum*. A similar project analyzed biodiversity in brownfield sites in Scotland and found they are also home to several rare invertebrates, including the bee *Andrena ruficrus* (Macadam and Bairner 2012). Brownfield sites are vulnerable because they are often among the first places to be transformed back to urban development (Goulson et al. 2011), so preserving them is a warranted conservation strategy.

Fly ash deposits from coal combustion on post-industrial sites have also been shown to be beneficial to pollinator communities in Europe. Only one study has investigated its use as pollinator habitat, and found these sites housed specialists and threatened species of bees and wasps, and contained a large number of arthropods in general (Troppek et al. 2014). Consideration must also be given to how contamination of industrial and post-industrial sites could negatively affect pollinators. For example, toxic impacts of metals such as aluminium, nickel and selenium on bees (e.g., Exley et al. 2015; Hladun et al. 2012, 2013, 2016; Meindl et al. 2013).

### Suggestions

Wild bee communities in urban areas are typically different from those found in natural areas, and are largely comprised of cavity nesters and exotic species. Bee abundance can be improved in urban areas by encouraging landowners to plant specific flowers in their window boxes and backyards and for cities to convert areas of land into botanical or community gardens. Native flowers are recommended from an ecological perspective, but urban bees do not show preference for native over exotic flowers, and often readily use both. Currently, bee hotels are not recommended as a tool for increasing bee populations in urban areas. Early research suggests that post-industrial areas, such as restored brownfield sites, can be suitable habitat for pollinators.

### Other Land Management Strategies

Other land management strategies, besides conservation efforts in agricultural and urban areas, can benefit pollinator populations. Maintaining and enhancing environments through prescribed burning, invasive plant removal, and restoring sensitive lands, can conserve habitat in the best state for pollinators. In addition, conservation strategies can aim to create new pollinator habitat, such as through restoring landfill sites to become wildflower meadows. Other emerging habitat creations are the areas beneath power lines, as well as long roadsides and railways, as they may serve as important refuges for bees. In Canada, it is estimated that 6,254 km<sup>2</sup> of potential pollinator habitat exists in the form of roadsides (Wojcik and Buchmann 2012). Hydro One power lines alone distribute throughout 75% of the province and cover approximately 10,406 km<sup>2</sup> of land in Ontario (O'Malley, pers. comm.). The transmission system map of Hydro One shows these lines transect through a variety of land types in Ontario (Hydro One Inc. 2006). Although some power lines are found in more wooded and shrubby areas that are not ideal for pollinators, others cross over meadows and grassier regions that would be. Determining new and innovative ways to create and maintain pollinator habitat is needed to help restore their populations in areas with high human-induced land use change.

### **Summary of Evidence**

There is no evidence from Ontario or Canada that investigates the impact of managed roadsides and power line habitat on pollinators. There is established but incomplete evidence from the USA and Europe that improving roadsides increases pollinator abundance (Hanley and Wilkins 2015) and often provides nest sites for rare species of bees (Russell et al. 2005; Wojcik and Buchmann 2012). Limited evidence suggests the level of traffic and width of road did not affect pollinator populations (Hopwood 2008), but more research should be conducted to ensure these habitats are safe for pollinators along busy highways in Ontario. Only one US study has investigated power line habitat for pollinators. The authors concluded that corridors that are not mowed, not treated with herbicides, but do have trees removed support the highest species richness and most rare bees compared to corridors subjected to other management practices (Russell et al. 2005). More research is needed to establish whether these corridors in Ontario could be suitable managed for pollinators.

Established but incomplete evidence from Ontario and the USA show prescribed burning is an effective conservation tool to restore pollinator populations (Taylor and Catling 2011; Van Nuland et al. 2013). Similarly, established but incomplete evidence from Ontario and Europe show transitioning landfills to pollinator habitat is also successful at promoting butterfly and bee populations (Rutgers-Kelly and Richards 2013; Tarrant et al. 2013). Restoring sensitive lands that are beneficial for pollinators, such as riparian land, rare sand dunes, and dry grasslands has been researched in a few case studies in the USA and Europe. However, there is no evidence for such attempts in Ontario, and research examining sensitive habitats required by the province's specific pollinator species is necessary to evaluate efficacy. Lastly, established but incomplete evidence from the US demonstrates that the improvement in bee populations following invasive species removal is immediate and profound, and leads to the restoration of specialist pollinator communities (Hanula and Horn 2011; Fiedler et al. 2012). Studies investigating the effect on pollinators from the removal of Ontario's invasive species are warranted.

### **Roadside and Power Line Habitat**

High bee diversity is traditionally reported along rights-of-way, road sides, and railway lines (Matheson et al. 1996), and these strips of land could also create corridors of connectivity between other bee habitats such as fields or gardens. Rare species are often found along these roadsides and rights-of-way (Russell et al. 2005; Wojcik and Buchmann 2012). In Ontario, individual power line companies decide how to manage the land beneath, and management strategies usually include periodic mowing (six times a year in Ontario), removing trees and thick shrub, or treating with herbicides (Hydro One Inc. 2009). These practices are targeted at reducing the likelihood of vegetation interfering with power lines, but simple modifications could make them ideal habitat for pollinators. A study in the Eastern USA examined whether improved habitat beneath power lines were better than mowed habitat beneath power lines for pollinators (Russell et al. 2005). The improved habitat was not mowed or treated with herbicides, and tall trees and shrubs were removed. The authors found the improved sites beneath power lines had significantly higher species richness and contained more rare bee species compared to mowed sites. The surrounding vegetation beyond the power lines was also found to influence the bee communities in these sites. The effect was positive if surrounding areas consisted of natural vegetation. Wojcik and Buchmann (2012) outlined the efficacy of land beneath power lines and along roadsides as pollinator habitat in a review paper. They concluded roadsides and power line ways can offer corridors of connectivity between larger pollinator habitats and can provide bee nesting sites.

Policies under the North American Electric Reliability Corporation are in place to routinely remove tall trees and shrubs to prevent them from interfering with the power lines (Hydro One Inc. 2009). The removal of this vegetation creates a more open pollinator-friendly habitat (Hanula et al. 2016). In Canada, power line companies must selectively remove trees or prune branches that may interfere with or fall on power lines or emergency right-of-way access. In areas where vegetation becomes too dense, power line companies must remove the vegetation and reseed the area with compatible ground cover plants. In some cases, power line companies may selectively treat trees or shrubs with herbicides instead of removing them (Hydro One Inc. 2009). The company Potomac Electric Power Company, in Maryland US, has taken the initiative to create a meadow management program for pollinators beneath their power lines (Vaughan et al. 2007). The US Fish and Wildlife Service has collaborated with this project and they have created six acres of wildflower habitat as a result. If companies in Ontario were required to shift their mowing regimes or sow seeds for pollinator-friendly plants in a similar manner to this case study, this could provide the province with 10, 406 km<sup>2</sup> of pollinator habitat.

Similar to vegetation beneath power lines, restoring roadsides with native plants provides nesting sites and forage for a variety of pollinators. Beekeepers have long recognized roadsides as good sources of flowers and often bring hives to roadsides during peak honey flows (Harper-Lore and Wilson 2000). Several studies have demonstrated the beneficial impacts of managed roadsides. A study in England found that bee abundance was over twice as high along roadsides than crop-adjacent margins (Hanley and Wilkins 2015). Fifty-seven roadsides were studied in the Netherlands to observe which pollinators were present (Noordijk et al. 2009). Eleven threatened bee species on the Dutch national Red List were found along these roadsides, and the overall presence of butterflies, hoverflies, and bees were higher than expected. In Kansas, restored roadsides had higher bee species richness and abundance compared to unmanaged roadsides that were left to grow wild (Hopwood 2008). Managed roadsides still had lower bee populations than nearby prairie

land, but they were significantly higher than unmanaged roadsides. The level of traffic and the width of the road did not have an effect on bee abundance or diversity, demonstrating that managing even the busiest highway sides could be beneficial to bees.

### **Prescribed Burning**

Fire management is a conservation tool for maintaining certain ecosystems that provide nesting habitat for bees through the removal of leaf litter and debris, and the encouragement of early successional plants for forage. Pollinators in alvar woodland and oak savannahs, among the most threatened habitats in Canada, benefit from prescribed burns. Taylor and Catling (2011) found species richness and pollinator abundance increased following fire in these landscapes. Another study (in the USA) found sites that were purposely burned experienced a 54% increase in pollinator visitation compared to unburned sites, due to an increase in native forbs establishing after a fire (Van Nuland et al. 2013). However, different functional guilds respond differently to fire. Ground nesters experience immediate positive impacts following fire due to the removal of leaf litter and the exposure of new soil, whereas cavity nesters and *Bombus* spp. experienced negative impacts from fire as their nesting sites are eradicated (Taylor and Catling 2011). Before implementing land management strategies, the ecology and life history of the targeted pollinators must be understood to predict their responses following fire.

### **Landfill Restoration**

Landfills can be restored to become ideal pollinator habitats that support similar levels of pollinators to natural fields. Rutgers-Kelly and Richards (2013) examined species diversity and abundance in a recently restored landfill in Southern Ontario. It was compared to one landfill restored ten years prior to the study, one restored 13 years prior, and a control meadow that had existed for over forty years. The highest species richness was seen in the most recently restored site and was nearly identical to the 13-year site and the control meadow. The highest abundance was in the recent site, followed by the control site and then the 13-year site. The authors conclude that the differences were likely due to the differences in floral species at each site, with the most blossoms available in the recent sites. Restored landfill sites are found to have comparable levels of species richness or abundance to natural reference sites in the UK (Tarrant et al. 2013). This conservation strategy is a low-cost, easily implemented strategy to enhance pollinator habitat.

### **Restoration of Sensitive Lands**

Studies have shown that restoring sensitive lands beneficial for pollinators, such as riparian land, rare sand dunes, and dry grasslands promotes pollinators. For example, The Nature Conservancy partnered with other NGOs in the USA to develop the Sacramento River Project. This project restored riparian vegetation along the Sacramento River, as this river has lost 95% of its original habitat due to agriculture and invasive species (Williams 2011). The project restored areas along the river and compared bee populations to nearby remnant riparian sites. Williams (2011) found no difference in overall abundance or species richness between restored and non-restored sites, showing that restoration allows the development of native bee communities similar to what is found at remnant riparian habitats. He found the bee communities between the two habitats varied; 17% of bee species were unique to the restored habitats and 18% were unique to the remnant habitats. Similarly, one study in Europe restored rare sand dunes and dry grasslands known to be ideal habitat for wild bees. Restoration of these habitats resulted in immediate increases in bee diversity and abundance (Exeler et al. 2009).

### **Invasive Plant Removal**

Habitat restoration in the form of removing invasive plant species also has profound implications on pollinator populations. After the removal of invasive glossy buckthorn in Michigan, new plant and pollinator communities rapidly colonized the area (Fiedler et al. 2012). In the first year following invasive plant removal, the pollinator community consisted of mainly generalist species and was similar to the community found in reference areas with no buckthorn found. Likewise, removing the invasive Chinese privet from riparian forests in Georgia led to a significant increase in wild bee abundance and diversity (Hanula and Horn 2011). Both of these studies from the USA demonstrate that the improvement in bee populations following invasive species removal is immediate.

### **Suggestions**

Land beneath power lines and along roadsides can provide good, connecting habitat (wildlife corridors) for pollinators. Ontario has 10,406 km<sup>2</sup> of open semi-natural land that could be more effectively managed to support bees, butterflies and other pollinators. Also, policies to manage the land along roadsides to incorporate pollinator-friendly flowers could be implemented. Prescribed burning is a tool already implemented in Ontario and is effective for promoting pollinators, however different guilds of pollinators respond differently to fires. The ecology and life history of the targeted pollinators should be determined on a case-by-base basis to predict their responses following prescribed burns. Removal of invasive species is another tool already being implemented in Ontario, and can provide immediate increases in pollinator populations. Lastly, there are few case studies examining the effects of restoring landfills and sensitive lands on pollinators. These existing studies report these practices are beneficial for pollinators, but more research is needed.

### **Pollinator Management Strategies**

The management of pollinators by humans can also be adjusted to enhance health and promote populations (see page 72 for details of management practices that positively and negatively impact these species). In Ontario honey bees, pests and pathogens, such as *Varroa* mites and the viruses they transmit are responsible for the majority of overwintering losses (Guzman-Novoa et al. 2010). Management practices that mitigate the infestation of *Varroa* are a main focus for increasing colony health. Although other managed bees in Ontario are not kept in hives and are not as domesticated as the honey bee, they too can be positively impacted by conservation practices.

### **Summary of Evidence**

Very few published studies outline specific management strategies that beekeepers can follow to maximize pollinator health. Integrated pest management strategies to reduce *Varroa* mites and colony disease are outlined in beekeeping manuals (such as the one published by Alten et al. 2013) and currently serve as the best resources to follow. More research is needed – specific to conditions in Ontario – to determine best management practices for honey bees. There is established but incomplete evidence from Ontario that increasing forage (through planting) and nest sites (through trap nests) around orchards increase managed BOB populations. There is no evidence on recommended management practices for the conservation of managed ALCBs or bumble bees.

### **Integrated Pest Management to Protect Bees**

In Ontario, honey bees have shown resistance to two out of the three synthetic chemicals registered to treat mites (fluvalinate and coumaphos). The third chemical, amitraz, continues to be effective in Ontario but mites have begun to show resistance in the USA (Kozak 2015a). It is crucial that beekeepers practice integrated pest management strategies to prevent resistance from developing for as long as possible. Integrated pest management strategies include rotating treatments between synthetic chemicals and organic chemicals (formic acid, oxalic acid, or thyme oil). In addition, beekeepers should use bees from a resistant genetic stock, such as hygienic bees or bees selected for grooming behaviour. Monitoring regularly for *Varroa* mites and disease ensures hives are treated as soon as possible. Other integrated management practices not involving chemical treatments can help keep pest levels low. These practices include 1) removing drone brood as these cells are the preferred type for varroa reproduction, 2) using a screened bottom board to catch mites that fall off bees and prevent them from crawling back into the hive, 3) interrupting brood rearing through colony splitting, and 4) re-queening when queens become old or decrease egg production (Alten et al. 2013).

In addition to varroa, resistance to oxytetracycline used to treat American foulbrood has been documented in the US, and there is a possibility that bees in Ontario may also become resistant soon. This increasing resistance to pests and pathogens warrants the establishment of integrated pest management strategies (Nasr and Kevan 1999) and research into new and effective treatments to target these pests and pathogens. Combining or rotating chemical treatments with natural treatments can help delay the onset of resistance.

### **Genetic Tools**

In addition to applying treatments to control pests and pathogens, genetic tools can be implemented as well. As outlined on page 62, several resistant and hygienic lines of honey bees have been bred for resistance to *Varroa* mites (Emsen et al. 2012; Guzman-Novoa et al. 2012), and tracheal mites (vanEngelsdorp and Otis 2001). Furthermore, RNAi techniques that reduce Israeli acute paralysis virus levels (Hunter et al. 2010; Maori et al. 2009), *Nosema ceranae* levels (Paldi et al. 2010), and varroa levels (Garbian et al. 2012) are also in the early stages of development.

### **Providing Forage and Nesting Sites**

A suggested strategy that has been met with success in Canada is providing additional food sources for the managed Blue Orchard Bee (BOB). The BOB is beginning to replace the honey bee as the managed pollinator in fruit orchards. Ensuring there is successional forage for BOBs to eat after the orchard flower blooms is necessary for their health and population stability. Sheffield and colleagues (2008b) examined the effect of planting nearby big leaf lupine (*Lupinus polyphyllus* Lindl. Fabaceae) as a secondary food source for BOBs in Nova Scotia. After orchard flowers finished blooming, big leaf lupine was the most predominant food source for BOB. Bees also increased in population size and the biggest population growth was seen in nests that were located within 600 m of big leaf lupine. This flower supports the population growth of BOB to meet pollination services required of orchards. The only downfall to using this plant as forage is that it is very expensive. More research into additional food source plants must be conducted that have similar traits: 1) a high preference by BOBs, and 2) overlap with and continuation of blooming after orchard flowers have finished. It is recommended that natural forage habitats be restored or created close to BOB nesting sites to provide additional forage for these bees in Ontario.

Providing nesting sites for managed bees has also been a successful management strategy. A study in Maine found the best way to increase managed blueberry bees (*Osmia atriventris*) for blueberry pollination is to set up many trap nests to encourage bees to nest nearby (Drummond and Stubbs 1997). However, this strategy is most successful when moderate levels of bees are introduced. The authors released over one thousand bees and found that in such high aggregations they did not use the trap nests and did not survive to the following seasons. Strategies need to be developed to encourage bees to nest in the hotels, and also to reduce parasitism levels once they have established.

### **Suggestions**

Research on human practices that benefit managed bees largely focus on reducing pests and diseases in the honey bee and promoting populations in other managed bees. In an attempt to postpone development of resistance to known effective pest and pathogen treatments, beekeepers should alternate using registered chemical treatments in addition to natural treatments, use bees from a resistant or hygienic stock, monitor their hives to know when (or if) to treat, and practice other behavioural strategies that reduce *Varroa* mite levels. Genetic tools for increasing bee health are beginning to emerge and may increase in importance in the future. *Varroa* resistant and hygienic lines of bees are available for purchase, but RNAi techniques to reduce disease levels are still under development.

Managed pollinators, other than honey bees, are beginning to be used widely to pollinate orchards, e.g. *O. lignaria*. The best strategies to increase their populations are to provide suitable forage plants (particularly for the period after the orchard bloom period has ended) and nesting sites. More research is needed to discover affordable flowers to plant and to determine how to use trap nests with greater success.

### **Public Interest and Citizen Science**

Garnering public interest is paramount for improving pollinator populations in Ontario, especially the southern regions that have intense levels of agriculture and urbanization. Worldwide, government protected lands and agri-environment schemes offer some protection for pollinators in farmlands and natural areas. However, a significant portion of land is residential property and its management is up to property owners. Educating the public on the importance of providing pollinator habitat can help support bees and butterflies in these areas. Human altered landscapes can still provide good foraging habitat for bees if we manage them properly.

### **Summary of Evidence**

Creatively educating the public about pollinators is assumed to inspire them to manage their land differently and to shift their ideologies toward wanting new government policies that protect them, however there are no empirical studies that quantitatively measure the behavioural outcomes due to increased awareness. There is well established evidence that citizen science projects that recruit volunteers to perform pollinator monitoring contribute to informative science (Biesmeijer 2012; Graham et al. 2014; Jue and Daniels 2015), and the results from these projects can and do shape conservation decision-making processes.



**Figure 24.** Examples of raising public awareness around bees. a) A sign posted in Toronto near a mining bee nest providing the public information on the requirements of this bee species and their ecological role. b) Signage placed in a Whole Foods Market grocery store in Medford, Massachusetts, illustrating the importance of bees for food production to customers.

### The Success of Engaging the Public

Raising public interest can help implement conservation strategies and motivate individuals to seek change. A recent survey showed European citizens place a high priority on pollinators and are willing to pay taxes to protect them (Breeze et al. 2015). Public interest can be raised through the media, with news stories and social media promoting pollinator awareness. Additionally, other actions can be taken to gain public interest, such as posting signs at pollinator gardens (Figure 24a), and labeling which foods are a direct result of animal pollination in grocery stores (Figure 24b). Creative educational and interacting features like these signs are a very economical way to instill interest by the public in pollinators.

Citizen science allows the public to engage in pollinator research and provides large sample sizes. Monitoring is fundamental in researching conservation strategies for pollinators, but widespread projects are time consuming and require many people. Engaging citizens to monitor bee abundance and diversity is an effective way to conduct research while gaining public interest. As mentioned earlier, citizen science efforts were very successful in monitoring the efficacy of bee hotels (Graham et al. 2014). Another large-scale citizen science study recorded the sites of bumble bee nests in the UK and determined which habitat was most preferred for nesting (Osborne et al. 2008). The most preferred sites were gardens and linear habitats in the countryside, including fence lines, forest edges, and hedgerows. Furthermore, an article in *Science* that demonstrated declines in pollinators and the plants they visit was based on a dataset largely built from citizen science records (Biesmeijer et al. 2006). Lastly, a statewide citizen science project in Florida has developed a butterfly database, which has already shaped conservation decision-making processes for species at risk (Jue and Daniels 2015). Initiatives such as Bumble bee Watch in Ontario, BeeWatch in Europe and BeeSpotter in the USA allow the public to take photos of bees and ID them to track their distributions.



### Suggestions

Outreach activities to educate and raise awareness of land owners, farmers, and the public are critical for improving pollinator health and biodiversity. Citizen science engaging the public (non-specialists) in pollinator research is gaining popularity. These programs can facilitate large-scale monitoring projects and the creation of useful databases that would otherwise not be created by individual scientists. However, citizen science projects must be designed appropriately to allow volunteers to contribute robust and usable data with little or no training requirements. Citizen science projects should therefore be considered as complimentary to, rather than replacements for, investigations by trained scientists.

### Conservation Organizations Promoting Pollinators

In addition to strategies tested in scientific studies, there are many organizations around the world that have programs targeted to promoting pollinators. Some government programs (in the USA and Europe) have conservation incentives for farmers, and have laws such as the Endangered Species Act (in Canada and the US) and the Endangered Species Programme (in Europe), and manage land through conservation areas and national parks. The majority of conservation organizations, however, are non-governmental organizations (NGOs) that independently raise money for research, pollinator habitat, and awareness. Despite the number of NGOs working to help preserve pollinators in Ontario, Canada, and worldwide, they do not own and manage enough land to sufficiently reverse pollinator declines on their own. It is imperative to recruit landowners and farmers to implement conservation strategies in order to have a significant impact, so outreach and education is a wide-reaching strategy (Goulson et al. 2011; Mawdsley and Humpert 2016). Table 10 outlines the conservation organizations and government involvement in Ontario, and it showcases the major organizations in Canada, the US, Europe, and Australia. Lastly, it presents the international initiatives that are in place to promote pollinators. This table briefly describes the goals and successes of these organizations, both past and present, and the type of work they are doing to impact pollinator health.

**Table 10.** Organizations throughout the world with conservation strategies for pollinators. The type of organization and the activities it is engaged in (e.g. monitoring, outreach, citizen science) are provided.

	Type of Organization	Pollinator Monitoring	Outreach	Citizen Science
Ontario	<b>Conservation Ontario</b>			
	Government	No	Yes	No
	<ul style="list-style-type: none"> <li>Represents the 36 conservation authorities in the province that span 147,000 hectares of protected and semi-protected land</li> <li>Manages natural resources, protect and restore ecosystems</li> <li>Provides natural, undisturbed habitat for pollinators to nest and forage within</li> <li>Monitors and control invasive plant species</li> <li>In 2012 conservation authorities worked with farm and non-farm landowners to restore 367 hectares of wildlife habitat. This includes providing technical support as well as access to financial assistance for cost-share</li> </ul>			

	<b>The Entomological Association of Ontario</b>			
	NGO	No	Yes	Yes
	<ul style="list-style-type: none"> <li>Developed in 1866 to further the study of entomology through meetings, events, and publications</li> <li>Creates outreach materials in the form of newspapers and the Journal of the Entomological Society of Ontario</li> <li>Holds events such as ‘Bug Day’ across Ontario for the public to come and learn about insects</li> <li>Includes the Toronto Entomologists’ Association</li> <li>Developed a citizen science project with Ontario Butterfly Atlas Online</li> </ul>			
	<b>Ontario Beekeepers Association</b>			
	Non-profit organization	Yes	Yes	No
Canada	<ul style="list-style-type: none"> <li>Main organization for honey bee industry information in Ontario</li> <li>Produces a magazine bimonthly for members and annual reports on bee research</li> <li>Manages Ontario Resistant Honey Bee Selection Program for pest- and disease-resistant bee breeding</li> <li>Advises policy members on new recommendations for honey bees</li> <li>Holds meetings to discuss relevant issues to beekeepers</li> <li>Supports the Tech-Transfer research program in Ontario</li> <li>Holds workshops for beginner and advanced beekeepers</li> </ul>			
	<b>Nature Conservancy of Canada (NCC)</b>			
	Non-profit organization	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Established in 1962 to protect, manage, and restore ecologically significant land</li> <li>Conserves over 2.7 million acres of land. Acknowledges that land they preserve, although not designated specifically for habitats, still serves as bee habitat</li> <li>Once a property is acquired, staff and volunteers document what species are found to aid in management decisions</li> <li>Participates in habitat management including invasive species removal and prescribed burning for the past ten years of the Rice Lake Plains in Northumberland County, which is beneficial to certain pollinators</li> <li>NCC’s Tall Grass Prairie Natural Area is used by researchers to study the decline of Poweshiek skipperling moth</li> <li>Developed a 5-year plan to restore 100 acres of agricultural land to Tall Grass Prairies to help monarch butterflies</li> <li>Provides information on bee biology, ecology, and pollination on the NCC blog. These posts include what you can do to help attract bees to your garden.</li> <li>Hosts events, workshops, and tours where the importance of pollination is emphasized</li> </ul>			

	<ul style="list-style-type: none"> <li>• 2013-2014 volunteers monitored butterflies on the Carden Alvar</li> <li>• Shares butterfly monitoring data with the North American Butterfly Association</li> </ul>			
	<b>Canadian Association of Professional Apiculturists (CAPA)</b>			
	NGO	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• Funds research on honey bee health and develops five-year research priorities</li> <li>• Inspects commercial bee colonies for diseases and pests</li> <li>• Collects statistics on provincial and federal honey and wax production</li> <li>• Leads conservation initiatives to encourage wild species of bees</li> <li>• Develop methods for sustainable beekeeping</li> <li>• Hosts conferences and meetings throughout Canada</li> </ul>			
	<b>Canadian Pollination Initiative (CANPOLIN)</b>			
	Universities, NGOs, and Government	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Developed a five-year initiative to address pollinator declines in Canada (2009-2014)</li> <li>• Improved knowledge and health of pollinators, and provided policy makers the tools to protect and conserve pollinators</li> <li>• Funded research projects, outreach activities, and graduate student theses</li> <li>• Helped develop Bumble bee Watch, a citizen science project</li> <li>• Produced newsletters, reports, manuals, and participated in several press releases</li> <li>• Published 131 articles</li> </ul>			
	<b>Wildlife Preservation Canada</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Helped develop the native pollinator program that includes Bumble Bee Watch <ul style="list-style-type: none"> <li>◦ Bumble Bee Watch uses citizen science to locate declining species and track invasive species. Photos are submitted online</li> </ul> </li> <li>• Produces outreach materials for the public including bee and butterfly brochures</li> </ul>			
	<b>Seeds of Diversity</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Founded in 1984</li> <li>• Involved in food sustainability and redesigning pollination strategies</li> <li>• Initiated 'Pollination Canada' project in 2004 to increase awareness of native bees to decrease reliance on honey bees for crop pollination</li> <li>• Successfully engages citizen science projects, but projects (two so far) were not successful in the long term</li> <li>• Develops outreach materials and holds public events</li> </ul>			

	<b>Pollinator Partnership</b>			
	NGO	No	Yes	No
	<ul style="list-style-type: none"> <li>• Largest organization in the world dedicated exclusively to protecting and promoting pollinators and their ecosystems. Has a Canadian Division and a US division</li> <li>• Developed interactive apps for the public and a pollinator curriculum for grade schools</li> <li>• Launches and participates in several projects to conserve pollinators <ul style="list-style-type: none"> <li>○ Wild for Bees (partnered with Burt's Bees and Toronto Fairmont Hotels to put bee hotels on roofs)</li> <li>○ Monarch Wings Across America (planting milkweed and nectar plants along migration corridors)</li> <li>○ SHARE (Planting for pollinators and then registering the planted area on the pollinator SHARE map)</li> <li>○ Pushed for the successful introduction of the Highways BEE Act (restoring pollinator habitat along highways)</li> <li>○ Funds Farm Bill provisions in the USA for farmers to restore pollinator habitat on agricultural lands</li> </ul> </li> </ul>			
	<b>Alternative Land Use Services (ALUS)</b>			
	NGO	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• First program to provide financial incentives to landowners that implement conservation benefits in Canada. ALUS offers annual stipends for farmers to convert up to 20% of their agricultural or environmentally sensitive land into wildlife habitat. Some of this habitat is beneficial for pollinators (e.g., planting pollinator hedgerows or restoring grasslands)</li> <li>• In 2007, the first project took place in Norfolk County, Ontario. By 2012, the program reached its full capacity of 50 new farms enrolling</li> <li>• Collaborates with researchers on their lands to publish articles about pollinator populations</li> <li>• Participating in 2015 bee monitoring project with the University of Guelph</li> <li>• Publishes outreach material about pollinator biology and ways the public can improve their populations through gardening</li> </ul>			
	<b>Environmental Monitoring and Assessment Network of Environment Canada (EMAN)</b>			
	Government, NGOs, and Universities	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Founded in 1994, EMAN is a national network of organizations involved in ecological monitoring of species in Canada</li> <li>• Launched the Pollinator Watch initiative, a citizen science Canadian monitoring program specific to pollinators <ul style="list-style-type: none"> <li>○ The program is successful in recruiting volunteers, but identifications are sometimes incorrect and require better training or verification by experts</li> </ul> </li> </ul>			

	<ul style="list-style-type: none"> <li>• Educates the public on the importance of pollination</li> <li>• Promotes multidisciplinary research for pollinators</li> </ul>			
	<b>Great Sunflower Project</b>			
	NGO	Yes	No	Yes
	<ul style="list-style-type: none"> <li>• Began in 2008 as the largest citizen science project focused on pollinators</li> <li>• Occurs in every Canadian province and every US state</li> <li>• Participants receive sunflower seeds to plant and then record the length of time it takes for five bees to visit a sunflower for a maximum time of 30 minutes to measure ‘pollinator service’</li> <li>• Gathers information about rural, urban, and suburban pollinator populations throughout North America</li> </ul>			
	<b>Honey Bee Health Coalition (HBHC)</b>			
	30 organizations and agencies from across food, agriculture, government, and conservation	No	Yes	No
USA	<ul style="list-style-type: none"> <li>• This organization spans Canada and the US</li> <li>• Constructed the “Bee Healthy Roadmap” that outlines how HBHC is going to improve honey bee health</li> <li>• Invests in the Tech-Transfer team that conduct monitoring and provide best management practices for beekeepers</li> <li>• Partners with initiatives to promote the registration of new varroacide products</li> <li>• Develops bee-friendly landscapes to supplement nutrition in agricultural areas in the upper Midwest of the US, transportation corridors and rights-of-way</li> <li>• Develops integrated pest management strategies to improve pollinator safety</li> <li>• Improves beekeeper incident reporting surrounding pesticide poisoning</li> <li>• Creates effective outreach tools for beekeepers and the public</li> </ul>			
	<b>BeeSpotter</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• A citizen science organization where volunteers take photos of bees in Illinois, Missouri, and Ohio and submit them online to be identified by experts</li> <li>• Photos can be taken from any place at any time, or can be more standardized and taken repeatedly at the same place at the same time for multiple years</li> <li>• Launched BeeBlitz, an annual 24-hour bee monitoring event during National Pollinator Week</li> </ul>			

	<b>American Museum of Natural History</b>			
	Museum	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Offers a Bee Course at the Southwestern Research Station in Portal Arizona every summer for biologists and ecologists to gain more knowledge of bees</li> <li>• Started a pilot citizen science program to recruit volunteers to collect data on bee sightings during National Pollinator Week</li> <li>• Operates the Center for Biodiversity and Conservation which translates the museum's scientific resources into conservation research, such as the Great Pollinator Project (GPP) <ul style="list-style-type: none"> <li>○ GPP teaches citizens about pollinators in New York City and develop ways to improve their habitat in urban areas</li> <li>○ Part of the GPP was Bee Watchers, where 50 volunteers monitored bees on certain flower species in New York City at specific times in summer and autumn</li> </ul> </li> </ul>			
	<b>Bee Informed Partnership</b>			
	9 universities, USDA-ARS, and Florida Department of Agriculture	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• Multi-university, multi-state project from a \$5 million, five-year grant from USDA</li> <li>• Uses epidemiology to improve honey bee management, survey winter colony loss, and develop best management practices for beekeepers</li> <li>• Maintains an interactive honey bee health database online</li> </ul>			
	<b>Conservation International</b>			
	NGO	No	Yes	No
	<ul style="list-style-type: none"> <li>• Combines science and partnerships with other organizations to protect nature. Has a particular interest in food and sustainable agriculture</li> <li>• Blogs about pollinator research and importance of pollinators</li> <li>• Partners with the Xerces Society on initiatives to protect and promote pollinators</li> <li>• Launched the Invertebrate Diversity Initiative that recognizes invertebrates as an important conservation priority</li> </ul>			
	<b>Defenders of Wildlife</b>			
	NGO	No	Yes	No
	<ul style="list-style-type: none"> <li>• Founded in 1947 to protect and restore key species and habitats</li> <li>• Helps private landowners manage their lands for biodiversity</li> <li>• Its sister organization 'Defenders of Wildlife Action Fund' works to influence government legislation directly</li> <li>• Publishes several blog posts about the importance of pollinator diversity and native bees</li> <li>• Holds petitions to protect pollinators (e.g., petition to the US Environmental Protection Agency urging to refuse the approval of</li> </ul>			

	harmful insecticides)			
	<b>McGuire Center for Lepidoptera and Biodiversity</b>			
	Museum	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• Serves for conducting research and educating the public</li> <li>• Research from this institution contributes to several peer-reviewed publications</li> <li>• Conducts research on habitat needs, conservation, and captive propagation of endangered butterfly species</li> <li>• Partners with local elementary schools to install butterfly gardens</li> </ul>			
	<b>NatureServe</b>			
	NGO	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• Provides a scientific basis for effective conservation action</li> <li>• 1000 conservation professionals working together from the Canada, the US, and South America</li> <li>• Forms over 80 network biodiversity centers throughout North and South America</li> <li>• The network collects, analyses, and distributes data about plants, animals, and ecosystems in their areas</li> <li>• Created 9 interactive online data tools and published over 2,000 peer-review publications. Among them is the ‘Conservation status assessment methodology’ to determine monarch butterfly status in North America</li> <li>• Partners with over 5,000 organizations for conservation and has a budget of \$60 million for conservation efforts</li> <li>• Assessed over 70,000 species including pollinators. Created distribution maps of five pollinator species</li> <li>• Holds webinars and conferences and creates newsletters that regularly feature pollinators</li> <li>• Advised a White House initiative to develop a national strategy on the health pollinators, including monarch butterflies</li> <li>• Advised state agencies to include specific plants (e.g., milkweed) in their 10-year strategies for conserving pollinators</li> <li>• Partnered with Xerces to write a report on the status of monarch butterflies in North America. Results were published by the US Forest Service</li> </ul>			
	<b>Oregon Zoo</b>			
	Zoo	No	Yes	No
	<ul style="list-style-type: none"> <li>• Conducts research on habitat needs and captive breeding programs for endangered butterflies <ul style="list-style-type: none"> <li>○ Together with its conservation partners, the zoo is planting the Oregon threatened silverspot butterfly’s native range with its host plant, the western blue violet</li> <li>○ The zoo is rearing and releasing the endangered Taylor’s checkerspot butterfly to build their populations in their historic prairie ranges</li> </ul> </li> </ul>			

	<b>US Department of Agriculture Farm Service Agency</b>			
	Government	No	Yes	No
	<ul style="list-style-type: none"> <li>Provides conservation incentives to farmers in the form of agri-environment schemes (AKA Farm Bill programs) that directly or indirectly benefit pollinators:               <ul style="list-style-type: none"> <li>Conservation Reserve Program</li> <li>Environmental Quality Incentives Program</li> <li>Wetlands Reserve Program</li> </ul> </li> <li>In 2012, joined the US Environmental Protection Agency to create a bee health task force to develop a plan to help prevent further pollinator declines</li> </ul>			
	<b>U.S. Department of Agriculture Natural Resource Conservation Service</b>			
	Government	No	No	No
	<ul style="list-style-type: none"> <li>Works with landowners to help conserve and improve natural resources on their land. Pollinator habitat is a priority in these natural resources since the 2008 Farm Bill</li> </ul>			
	<b>North American Pollinator Protection Campaign (NAPPC)</b>			
	Academics, policy makers, government, industries	Yes	Yes	No
	<ul style="list-style-type: none"> <li>Established in 1999 by Pollinator Partnership collaborating with the National Fish and Wildlife Foundation with the goal to conserve pollinator populations</li> <li>Co-ordinates with existing programs to conserve habitat and migratory corridors</li> <li>Promotes and supports pollinator research</li> <li>Holds annual conferences in Washington to develop plans for pollinator protection</li> <li>Along with Xerces, developed the Pollinator Protection Act and the Pollinator Habitat Protection Act</li> <li>Helped to accomplished the first ever provision for pollinators in the 2008 US farm bill</li> <li>Introduced a pollinator program in the curriculum for grade 3-6</li> <li>Successfully advocated for the US Senate to designate the last week in June as National Pollinator Week</li> <li>Promotes education and awareness and presents awards to individuals whose actions have helped pollinators</li> <li>Produces informative brochures on bees for the public in collaboration with other organizations</li> <li>Five-year project to research and protect migratory pollinators (birds, bats, and butterflies)</li> <li>Research combined with identifying, preserving, and restoring migratory corridors and major stopover sites</li> <li>In addition to these efforts, the authors stress that reducing pesticides,</li> </ul>			



	creating government policies, and establishing financial incentives for farmers to participate in ecological restoration projects is imperative			
	<b>Xerces Society</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Established in 1971, it is the largest organization exclusively devoted to invertebrate conservation</li> <li>Identifies and promotes the protection of invertebrates on the Endangered Species Act</li> <li>Protects endangered species and their habitat, produced books on insect conservation, trains farmers and land managers to protect and manage habitat for invertebrates</li> <li>Works with federal agencies to develop policies that protect pollinators in their conservation programs (such as incorporating pollinator conservation in the Farm Bill in the form of the Pollinator Protection Act and the Pollinator Habitat Protection Act)</li> <li>Organized a citizen science survey for the rusty-patched bumble bee through online photo submission, and the citizen-science pollinator monitoring program 'Pennsylvania Native Bee Survey'</li> <li>Together with Natural Resource Defense Council and Defenders of Wildlife and other NGOs, petitioned the USDA to regulate movement of bumble bees in the U.S. in order to certify them disease-free and keep them within their native range</li> <li>Implements the Yolo Natural Heritage Program pollinator conservation strategy in Yolo County, California</li> <li>Developed a Monarch Conservation Campaign to conserve overwintering sites in California and restore milkweed habitats for breeding</li> </ul>			
	<b>Monarch Watch</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Promotes monarch butterfly conservation through a network of students, teachers, volunteers and researchers</li> <li>Initiated the Monarch Waystation Program, which plants stopping habitats with milkweed and nectar sources along migration routes</li> <li>Provides free milkweed to schools</li> <li>Performs monitoring and tagging and also leads citizen science monitoring projects</li> </ul>			
	<b>Saint Louis Zoo's WildCare Institute Center for Native Pollinator Conservation</b>			
	Zoo	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Educates people on the importance of pollinators, developing and collaborating on projects for pollinator conservation</li> <li>Produced the first identification guide for bumble bees in Illinois and Missouri in 2008, and produces other guides for students, farmers, researchers, and citizen scientists</li> <li>Conducts bee surveys to examine diversity and abundance and</li> </ul>			

	<p>identify areas of concern</p> <ul style="list-style-type: none"> <li>• The center works with community garden groups like Gateway Greening to educate individuals about native bees and teach gardeners what to plant to attract bees</li> <li>• Partnered with Xerces in 2010 to develop pollinator rights-of-way through improving roadsides and developing pollinator gardens at rest areas and welcome centers</li> <li>• In 2013, initiated the PAUSE project in collaboration with other individuals and programs to design and establish pollinator gardens</li> <li>• The zoo has partnered with the City of St. Louis to increase monarch populations through planting monarch gardens</li> <li>• Created the ‘Adopt a Monarch Butterfly’ program where you can buy kits for planting a monarch garden and learn about monarchs</li> </ul>			
	<b>Pollinator Stewardship Council</b>			
	NGO	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• Influences the regulatory process of pesticides and labeling <ul style="list-style-type: none"> <li>○ Submitted comments to federal committee regarding different bills, like ‘Secret Science’ H.B. bill 4017</li> <li>○ Participated in federal committees for the Environmental Protection Agency and the Society of Environmental Toxicology and Chemistry</li> </ul> </li> <li>• Set up meetings with EPA and beekeepers after the almond pollination bee kill in California in 2014 to report findings and improve communication</li> <li>• Provides tools to document the harmful effects of pesticides</li> <li>• Collects pollinator kill reports from beekeepers in several states every year</li> <li>• Presents at conferences and seminars</li> <li>• Runs the Hive Tracking Project with Pesticide Research Institute to monitor pesticide and pathogen levels in 60 beehives</li> </ul>			
	<b>Project Apis m.</b>			
	NGO	No	Yes	No
	<ul style="list-style-type: none"> <li>• Began in 2006</li> <li>• Funded \$2.5 million into bee research</li> <li>• Provides outreach in the form of best management practices and information to growers and beekeepers</li> <li>• Holds educational outreach events</li> </ul>			
	<b>Haagen-Dazs</b>			
	For-profit business	No	Yes	No
	<ul style="list-style-type: none"> <li>• In 2008, partnered with leading research facilities to donate more than \$1 million to honey bee research and created a Haagen Dazs honey bee demonstration garden on the UC Davis campus</li> </ul>			

Europe	<b>Assessing Large Scale Risks for Biodiversity with Tested Methods (ALARM) Project</b>			
	Government	Yes	Yes	No
	<ul style="list-style-type: none"> <li>Initiative throughout 30 countries largely in Europe, but also includes Africa and South America. Funded by the European Union</li> <li>Monitors wild bees and syrphid flies to provide a large-scale risk assessment</li> <li>Establishes economic impacts of biodiversity loss as a tool to inform policy makers</li> <li>Stresses the importance of maintaining curated collections</li> <li>Quantifies pollinator distribution shifts across Europe</li> <li>Measures biodiversity and economic risks associated with the loss of pollination services in agricultural and natural systems through the development of standardized tools and protocols</li> <li>Determines the importance of drivers of pollinator loss (i.e., land use, climate change, environmental chemicals, invasive and socio-economic factors)</li> <li>Provided an assessment of the declines in pollinators and their associated plants in Europe to the European Union</li> <li>Maintains an online database on pollinators of Europe</li> <li>Develops predictive models for pollinator loss and consequent risks</li> <li>Shares scientific findings on ALARM News on website, through radio interviews, scientific publications, and conferences</li> </ul>			
	<b>Bybi</b>			
	NGO	No	Yes	Yes
	<ul style="list-style-type: none"> <li>In 2015 announced the world's first 'bee highway' to run through Oslo Norway to provide a safe transport corridor through the city for urban bees</li> <li>Community project that involves schools, businesses, organizations, government buildings, and residents to plant forage (e.g., green roofs, floral gardens) or set up bee hotels</li> <li>Participants attach a photo of their contribution and tag it with geographical coordinates on a map</li> <li>Website provides outreach material in the form of information on pollinators and what species of plants attract bees</li> </ul>			
	<b>Hymettus Ltd</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Began in 1997 and operates in the UK</li> <li>Funds research and provides advice and expertise relating to the conservation of bees, wasps, and ants</li> <li>Establishes forage in field margins, reintroduces at-risk species, and participates in monitoring projects to help bee conservation</li> <li>In May 2014 reintroduced queen <i>Bombus subterraneus</i> bees from Sweden to the UK</li> <li>Performs monitoring of different species of invertebrates and of <i>Osmia</i> species throughout the UK</li> </ul>			

	<ul style="list-style-type: none"> <li>• Participated in the five-year Species Action Framework project that was completed in 2012 to educate the public, to develop demonstration plots, and to monitor bees</li> <li>• Supports three projects funded under the Insect Pollinator Initiative: ‘Impact and Mitigation of Emergent Diseases on Major UK Insect Pollinators’, ‘Linking Agriculture and Land Use Change to Pollinator Populations’, and ‘Sustainable Pollination Services for UK Crops Lead’</li> <li>• Provides outreach material in the form of information sheets and pamphlets with pollinator information and bee friendly gardening advice</li> </ul>			
	<b>Bees, Wasps &amp; Ants Recording Society</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Operates in Britain and Ireland</li> <li>• Started as an initiative under the International Bee Research Association in 1978</li> <li>• Subscription-based volunteer monitoring of the changing distributions of bees, wasps, and ants</li> <li>• There are currently about 500 members</li> <li>• Submitted monitoring records must be accompanied by samples or species identifications verified by experts</li> <li>• Organizes specific monitoring projects such as the ‘Winter Bumble Bees Project’ for winter activity of <i>Bombus terrestris</i>, and creating atlases and maps of aculeate ranges, a survey of bees and wasps in grassland sites of East Sussex Downs, and a trap-nesting project to monitor <i>Stelis phaeoptera</i> in Shropshire</li> <li>• Also participates in STEP</li> <li>• Contains information on their website about the biology of aculeates, information sheets to download, and species lists</li> <li>• Provides advice and training to members and the general public</li> </ul>			
	<b>Operation Pollinator</b>			
	For-profit Business	Yes	No	No
	<ul style="list-style-type: none"> <li>• Initiated in 2010 by the pesticide company Syngenta, this UK project ‘Operation Pollinator for Golf Courses’ planted perennial wildflowers in out-of-play areas for pollinator habitat</li> <li>• Gives UK and Ireland golf course managers the tools to establish and manage wildflower resources. Guidelines were developed with ecologists and agronomists from the Sports Turf Research Institute</li> <li>• An assessment of the project’s efficacy identified forty-nine species in planted wildflowers on five established golf courses, including three rare, declining bee species.</li> </ul>			

	<b>European Association for Bee Research (EurBee)</b>			
	NGO	No	No	No
	<ul style="list-style-type: none"> <li>• Holds conferences on bee research every two years and distributes newsletters on research collaborations and upcoming meetings</li> </ul>			
	<b>Bumble Bee Conservation Trust</b>			
	NGO	No	Yes	No
	<ul style="list-style-type: none"> <li>• Formed in the United Kingdom in 2006 to prevent the extinction of UK's bumble bees, to restore their habitat, and to increase awareness about bees. There are over 8,000 members</li> <li>• Focuses on translating bumble bee ecology research into conservation practices</li> <li>• Distributed &gt;20,000 packages of wildflower seeds, collaborates with garden centres to promote bumble bee friendly plants for sale, and has educated the public with booklets and running information booths at flower shows</li> <li>• In 2012, launched its national 'Bees for Everyone' project to raise awareness for bees and create habitat</li> <li>• Has exhibits at public events, hold training courses for identification and guided walks</li> <li>• Currently calling for a ban on neonicotinoids indefinitely in Europe</li> <li>• Leading the 'Short-Haired Bumble Bee Project' which reintroduces the extinct species to the UK and creates flower-rich grassland for its habitat</li> </ul>			
	<b>Status and Trends of European Pollinators (STEP) project</b>			
	24 organizations throughout 21 European countries	Yes	No	No
	<ul style="list-style-type: none"> <li>• A five-year project coming out of the European Pollinator Initiative that aims to determine the status and trends of pollinators in Europe</li> <li>• The project began in 2010 and is funded by the European Commission</li> <li>• Determines what factors are influencing these trends, identifies and evaluates conservation strategies to help pollinators, and increases communication about pollinators among policy makers, beekeepers, farmers, scientific researchers, and the public</li> <li>• Developed the first continental Red Data Book for bees</li> <li>• Implements a pollinator monitoring program throughout Europe</li> <li>• Published several peer-reviewed articles</li> <li>• Identified the conservation status of pollinators on the Red List</li> </ul>			
	<b>European Union Common Agricultural Policy</b>			
	Government	No	Yes	No
	<ul style="list-style-type: none"> <li>• Provides support to beekeepers through apiculture programs and rural development programs both financially and through training/advice</li> <li>• Enforces mandatory 'greening' of farms, as well as crop diversification and the introduction of ecological focus areas. These practices indirectly help pollinators</li> </ul>			

	<b>Insect Pollinators Initiative (UK)</b>			
	Government and Industry	No	No	No
	<ul style="list-style-type: none"> <li>• Provided \$20M toward nine projects that examine pollinators in urban and natural environments</li> <li>• Engages with policy makers, farmers, growers, NGOs, and other stakeholders who have an interest in pollination</li> </ul>			
	<b>National Pollinator Strategy (UK)</b>			
	Government	Yes	No	No
	<ul style="list-style-type: none"> <li>• Implements United Kingdom's large scale monitoring project</li> <li>• Works with farmers to support pollinators through the Common Agricultural Policy</li> <li>• Recommends integrated pest management practices to reduce exposure of pesticides to pollinators to farmers and other stakeholders</li> <li>• Encourages pollinator habitat for large-scale private lands, public lands, brownfields, and the general public's lands</li> <li>• Improves the communication of scientific evidence to conservation organizations and NGOs</li> </ul>			
	<b>Bees in Europe and the Decline of Honey Bee Colony Losses (BEE DOC)</b>			
	University and Industry	No	No	No
	<ul style="list-style-type: none"> <li>• Focuses on honey bee pathogens, pesticides, and their interactions</li> <li>• A network of 11 partners that conduct research</li> <li>• Over 80 publications have resulted from research of scientists associated with BEE DOC</li> </ul>			
	<b>BeeNet</b>			
	Government and University	Yes	No	No
	<ul style="list-style-type: none"> <li>• National large-scale honey bee monitoring project in Italy</li> <li>• Studies environmental interactions, disease prevalence, and mortality</li> <li>• Includes over 3000 hives in over 300 apiaries</li> <li>• Initiated the Bee Emergency Service Team to study unidentified bee mortality in real time</li> </ul>			
	<b>European Pollinator Initiative</b>			
	Government and University	Yes	No	No
	<ul style="list-style-type: none"> <li>• Subset of the International Pollinator Initiative</li> <li>• Uses the scientific evidence base to develop policies and practices to conserve pollinators</li> <li>• Conducts pollinator research <ul style="list-style-type: none"> <li>○ Monitors pollinators throughout Europe and assesses the economic value of pollination and of the decline of pollination services</li> <li>○ Provides more taxonomic information on pollinators</li> </ul> </li> </ul>			

	<ul style="list-style-type: none"> <li>Developed the project STEP (Status and Trends of European Pollinators) to address the stresses causing pollinator declines</li> </ul>			
Australia	<b>Australia Department of Agriculture</b>			
	Government	No	No	No
	<ul style="list-style-type: none"> <li>Australia has developed a honey bee and pollination continuity strategy to prevent varroa introduction and to act quickly should varroa become established</li> <li>Has the ‘National Landcare Program’ and ‘Conservation Reserve Program’ in place for farmers <ul style="list-style-type: none"> <li>These programs are agri-environment schemes that drive sustainable agriculture and restore/conserv natural habitat like shrublands, grasslands, and forests on farmland that benefit pollinators indirectly</li> </ul> </li> </ul>			
International Initiatives	<b>International Union for Conservation of Nature (IUCN)</b>			
	International Organization	No	Yes	No
	<ul style="list-style-type: none"> <li>Founded in 1948 and is now the largest global conservation network that influences international government policies and laws</li> <li>Supports field conservation projects all over the world that conserve wildlife habitat, indirectly benefiting pollinators</li> <li>Collaborates on many scientific publications and reports relating to pollinators <ul style="list-style-type: none"> <li>Published ‘Global trends in the status of bird and mammal pollinators’ in the journal Conservation Letters</li> <li>Involved in the production of ‘Worldwide Integrated Assessment of the Impacts of Systemic Pesticides on Biodiversity and Ecosystems’ report. Written by the Task Force on Systemic Pesticides but is affiliated with the IUCN. The report analyzed 800 peer-reviewed papers on neonicotinoids and concluded they are harmful to pollinators and other wildlife</li> </ul> </li> <li>Created the IUCN Red List of Threatened Species, the definitive international standard for species extinction risk</li> <li>Created the IUCN Bumble bee specialist group in 2011 to assess the status of all bumble bee species declines around the world</li> <li>Produces monthly newsletters that sometimes feature pollinators</li> </ul>			
	<b>DiscoverLife</b>			
	NGO	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>Provides online tools to identify species and teaches the general public about nature through demonstrations</li> <li>Built an interactive online encyclopedia with species and their native ranges</li> <li>In the process of digitizing a map of pollinators from curated samples in the US to examine how environmental changes affect life history and pollination</li> </ul>			

	<ul style="list-style-type: none"> <li>• Posts accessible online ID guides for wasps and bees</li> <li>• Organized a ‘Bee Hunt’ for citizen science to understand the impacts of climate change on plant-pollinator interactions and bee abundance. The monitoring project is accomplished through taking photographs of bees and submitting them online</li> <li>• Contributes to peer-reviewed scientific publications</li> </ul>			
	<b>International Commission for Plant-Pollinator Relationships (ICPBR)</b>			
	NGO	No	No	No
	<ul style="list-style-type: none"> <li>• Founded in 1950 to promote research on the relationships between plants and bees</li> <li>• Collaborates with national and international institutions that conduct pollinator research</li> <li>• Holds symposiums to showcase pollinator research and publishes conference proceedings</li> </ul>			
	<b>The Prevention of Honey Bee Colony Losses (COLOSS)</b>			
	NGO	Yes	Yes	No
	<ul style="list-style-type: none"> <li>• International European-funded program with 212 members from 52 countries, focused on improving the health of honey bees at a global level. The members consist of researchers, veterinarians, agriculture extension specialists and students from 69 countries</li> <li>• Runs a colony loss monitoring program</li> <li>• Developed two volumes of COLOSS BeeBook, which outlines standard methods for bee research</li> <li>• Holds conferences for showcasing honey bee research</li> <li>• Developed the ‘Core Project’, which reaches out to beekeepers to provide them with resources and tools to maximize bee health</li> </ul>			
	<b>APIMONDIA</b>			
	NGO	No	No	No
	<ul style="list-style-type: none"> <li>• International federation of beekeepers association</li> <li>• Founded in 1949 with the objective to facilitate information exchange and discussions to promote apicultural development in all countries</li> <li>• Holds international conferences and meetings</li> </ul>			
	<b>International Pollinator Initiative</b>			
	Governments	Yes	Yes	Yes
	<ul style="list-style-type: none"> <li>• Originated in 2000 from the United Nations Convention on Biological Diversity to address the worldwide decline in pollinators</li> <li>• A plan of action was developed and adopted in 2002</li> <li>• Promotes monitoring pollinators, contributes taxonomic information on pollinators, assesses economic values of values of pollination, and promotes conservation of pollinator diversity</li> <li>• Has prepared two reports on pollinator status</li> <li>• Created the ‘World Bee Checklist’ of all known species in the world uploaded on the Integrated Taxonomic Information System database</li> <li>• Provides resources for farmers, handbooks for protocols for pollinator</li> </ul>			



	<p>monitoring, and keys to identify bees</p> <ul style="list-style-type: none"><li>• Develops tools and resources for farmers and beekeepers to promote sustainable agriculture</li></ul>
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## REFERENCES

- Abbott VA, Nadeau JL, Higo HA, Winston ML (2008) Lethal and sublethal effects of imidacloprid on *Osmia lignaria* and clothianidin on *Megachile rotundata* (Hymenoptera: Megachilidae). *Journal of Economic Entomology* 101:784-96. doi:10.1603/0022-0493(2008)101[784:laseoi]2.0.co;2
- Abrol DP (2012a) Climate change and pollinators. pp. 479-508 in *Pollination Biology: Biodiversity Conservation and Agricultural Production*. Springer, Houten, Netherlands.
- Abrol DP (2012b) Consequences of introduced honeybees upon native bee communities. pp. 635-667 in *Pollination Biology: Biodiversity Conservation and Agricultural Production*. Springer, Houten, Netherlands.
- Abrol DP (2012c) Capacity building and awareness for pollinators. pp. 771-785 in *Pollination Biology: Biodiversity Conservation and Agricultural Production*. Springer, Houten, Netherlands.
- Adamson NL, Roulston, TH, Fell RD, Mullins, DE (2012) From april to august-wild bees pollinating crops through the growing season in Virginia, USA. *Environmental Entomology* 41:813-821. doi:10.1603/en12073
- Ahrne K, Bengtsson J, Elmqvist T (2009) Bumble bees (*Bombus* spp) along a gradient of increasing urbanization. *PLoS One* 4:e5574. doi:10.1371/journal.pone.0005574
- Aizen MA, Harder LD (2009) The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. *Current Biology* 19:915-918. doi:10.1016/J.Cub.2009.03.071
- Aizen MA, Garibaldi LA, Cunningham SA, Klein AM (2009) How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. *Annual Review of Botany* 103:1579-1588. doi:10.1093/aob/mcp076
- Alaux C, Brunet JL, Dussaubat C, Mondet F, Tchamitchan S, Cousin M, Brillard J, Baldy A, Belzunces LP, Le Conte Y (2010a). Interactions between *Nosema* microspores and a neonicotinoid weaken honeybees (*Apis mellifera*). *Environmental Microbiology* 12:774-782. doi:10.1111/j.1462-2920.2009.02123.x
- Alaux C, Ducloz F, Crauser D, Le Conte Y (2010b) Diet effects on honeybee immunocompetence. *Biology Letters* 6:562-565. doi:10.1098/Rsbl.2009.0986
- Albano S, Salvado E, Borges PAV, Mexia A (2009) Floral visitors, their frequency, activity rate and index of visitation rate in the strawberry fields of Ribatejo, Portugal: selection of potential pollinators. Part 1. *Advances in Horticultural Science* 23:238-245.
- Albrecht M, Duelli P, Mueller C, Kleijn D, Schmid B (2007) The Swiss agri-environment scheme enhances pollinator diversity and plant reproductive success in nearby intensively managed farmland. *Journal of Applied Ecology* 44:813-822. doi:10.1111/j.1365-2664.2007.01306.x
- Alford DV (1975) *Bumblebees*. David-Poynter, London, UK.
- Alhaddad S, Darchen B (1995) The influence of meteorological conditions on the feeding and egg-laying of the queen honey bee. *Comptes Rendus de L'Academie des Sciences Series III-Sciences de la Vie-Life Sciences* 318:245-248.

Allen-Wardell G, Bernhardt P, Bitner R, Burquez A, Buchmann S, Cane J, Cox PA, Feinsinger P, Ingram M, Inouye D et al. (1998) The potential consequences of pollinator declines on the conservation of biodiversity and stability of food crop yields. *Conservation Biology* 12:8-17.

Allsopp MH, de Lange WJ, Veldtman R (2008) Valuing insect pollination services with cost of replacement. *PLoS One* 3:e3128. doi:10.1371/journal.pone.0003128

Almeida-Muradian, LB, Pamplona LC, Coimbra S, Barth MO (2005) Chemical composition and botanical evaluation of dried bee pollen pellets. *Journal of Food Composition and Analysis* 18:105-111.

Alston DG, Tepedino VJ, Bradley BA, Toler TR, Griswold TL, Messinger SM (2007) Effects of the insecticide phosmet on solitary bee foraging and nesting in orchards of Capitol Reef National Park, Utah. *Environmental Entomology* 36:811-816. doi:10.1603/0046-225x(2007)36[811:eotipo]2.0.co;2

Altieri M (1977) The ecological role of weeds in insect pest management systems: a review illustrated by bean (*Phaseolus vulgaris*) cropping systems. *International Journal of Pest Management* 23:195-205.

Altieri M, Nicholls C (2004) *Biodiversity and Pest Management in Agroecosystems*. CRC Press, Boca Raton, Florida, USA.

Altikrit W, Clarke WW, McKee GW, Risius ML, Peiffer RA (1974) Days from pollination to seed maturity in crownvetch. *Crop Science* 14:527-529.

Altshuler D (1999) Novel interactions of non-pollinating ants with pollinators and fruit consumers in a tropical forest. *Oecologia* 119:600-606.

Amaya-Marquez M, Hill PSM, Barthell JF, Pham LL, Doty DR, Wells H (2008) Learning and memory during foraging of the blue orchard bee, *Osmia lignaria* Say (Hymenoptera: Megachilidae). *Journal of the Kansas Entomological Society* 81:315-327. doi:10.2317/jkes801.29.1

Ambrose JT, Stanghellini MS, Hopkins DI (2000) A scientific note on the threat of small hive beetles (*Aethina tumida* Murray) to bumble bee (*Bombus* spp.) colonies in the United States. *Apidologie* 31:455-456.

Amdam GV, Norberg K, Omholt SW, Kryger P, Lourenco AP, Bitondi MMG, Simoes ZLP (2005) Higher vitellogenin concentrations in honey bee workers may be an adaptation to life in temperate climates. *Insectes Sociaux* 52:316-319. doi:10.1007/s00040-005-0812-2

Anderson DL (1995) Viruses of *Apis cerana* and *Apis mellifera*. pp. 161-170 in *The Asiatic Hive Bee: Apiculture, Biology, and Role in Sustainable Development in Tropical and Subtropical Asia*. Ed. Kevan PG. Enviroquest, Cambridge, Ontario, Canada.

Anderson DL, Giacon H (1992) Reduced pollen collection by honey bee (Hymenoptera, Apidae) colonies infected with *Nosema-Apis* and Sacbrood Virus. *Journal of Economic Entomology* 85:47-51.

Anderson R (2009) A 2-year small grain interval reduces need for herbicides in no-till soybean. *Weed Technology* 23:398-403.

Anderson R (2010) Rotation design: a critical factor for sustainable crop production in a semiarid climate: a review. pp. 107-121 in *Organic Farming, Pest Control and*

*Remediation of Soil Pollutants Sustainable Agriculture Reviews*. Springer, Houten, Netherlands.

Andersson GKS, Rundlöf M, Smith HG (2012) Organic farming improves pollination success in strawberries. *PLoS One* 7:e31599. doi:10.1371/journal.pone.0031599.g001

Andrearczyk S, Kadhim MJ, Knaga S (2014) Influence of a probiotic on the mortality, sugar syrup ingestion and infection of honey bees with *Nosema* spp. under laboratory assessment. *Medycyna Weterynaryjna-Veterinary Medicine-Science and Practice* 70:762-765.

Andren H (1994) Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos* 71:355-366.

Andrews ES, Theis N, Adler LS (2007) Pollinator and herbivore attraction to *Cucurbita* floral volatiles. *Journal of Chemical Ecology* 33:1682-1691. doi:10.1007/s10886-007-9337-7

Annoscia D, Del Piccolo F, Nazzi F (2012) How does the mite *Varroa destructor* kill the honey bee *Apis mellifera*? Alteration of cuticular hydrocarbons and water loss in infested honey bees. *Journal of Insect Physiology* 58:1548-1555. doi:10.1016/j.jinsphys.2012.09.008

Antunez K, Martin-Hernandez R, Prieto L, Meana A, Zunino P, Higes M (2009) Immune suppression in the honey bee (*Apis mellifera*) following infection by *Nosema ceranae* (Microsporidia). *Environmental Microbiology* 11:2284-2290. doi:10.1111/j.14622920.2009.01953.x

Araújo MB, Ferri-Yáñez F, Bozinovic F, Marquet PA, Valladares F, Chown SL (2013) Heat freezes niche evolution. *Ecology Letters* 16:1206-1219. doi:10.1111/ele.12155

Arce AN, David TI, Randall EL, Rodrigues AR, Colgan TJ, Wurm Y, Gill RJ (2016). Impact of controlled neonicotinoid exposure on bumblebees in a realistic field setting. *Journal of Applied Ecology* doi:10.1111/1365-2664.12792.

Archer CR, Pirk CWW, Carnevalheiro LG, Nicolson SW (2014) Economic and ecological implications of geographic bias in pollinator ecology in the light of pollinator declines. *Oikos* 123:401-407. doi:10.1111/j.1600-0706.2013.00949.x

Arechavaleta-Velasco ME, Guzman-Novoa E (2001) Relative effect of four characteristics that restrain the population growth of the mite *Varroa destructor* in honey bee (*Apis mellifera*) colonies. *Apidologie* 32:157-174.

Arechavaleta-Velasco ME, Alcala-Escamilla K, Robles-Rios C, Tsuruda JM, Hunt GJ (2012) Fine-scale linkage mapping reveals a small set of candidate genes influencing honey bee grooming behavior in response to *Varroa* mites. *PLoS One* 7:e47269. doi:10.1371/journal.pone.0047269

Arena M, Sgolastra F (2014) A meta-analysis comparing the sensitivity of bees to pesticides. *Ecotoxicology* 23:324-334. doi:10.1007/s10646-014-1190-1

Aronstein KA, Murray KD (2010) Chalkbrood disease in honey bees. *Journal of Invertebrate Pathology* 103:20-29. doi:10.1016/j.jip.2009.06.018

- Artz DR, Hsu CL Nault BA (2011) Influence of honey bee, *Apis mellifera*, hives and field size on foraging activity of native bee species in pumpkin fields. *Environmental Entomology* 40:1144-1158. doi:10.1603/en10218
- Ashman TL, Knight T, Steets J, Amarasekare P, Burd M, Campbell DR, Dudash MR, Johnston MO, Mazer SJ, Mitchell RJ, et al. (2004) Pollen limitation of plant reproduction: ecological and evolutionary causes and consequences. *Ecology* 85:2408-2421. doi:10.1890/03-8024
- Atkins E, Kellum D, Atkins K (1978) Integrated pest management strategies for protecting honey bees from pesticides. *American Bee Journal* 118:19-21.
- Atkins EL (1992) Injury to honey bee by poisoning. pp. 1153-1208 in *The Hive and the Honey Bee*. Ed. Graham JE. Dandant and Sons, Hamilton, Illinois, USA.
- Atwood CE (1933) Studies on the Apoidea of western Nova Scotia with special reference to visitors to apple bloom. *Canadian Journal of Research Ottawa* 9:443-157.
- Aufauvre J, Biron DG, Vidau C, Fontbonne R, Roudel M, Diogon M, Vigues B, Belzunces LP, Delbac F, Blot N (2012) Parasite-insecticide interactions: a case study of *Nosema ceranae* and fipronil synergy on honeybee. *Scientific Reports* 2:326. doi:10.1038/srep00326
- Backman J, Tiainen J (2002) Habitat quality of field margins in a Finnish farmland area for bumblebees (Hymenoptera: *Bombus* and *Psithyrus*). *Agriculture, Ecosystems & Environment* 89:53-68.
- Bailey J, Scott-Dupree C, Harris R, Tolman J, Harris B (2005) Contact and oral toxicity to honey bees (*Apis mellifera*) of agents registered for use for sweet corn insect control in Ontario, Canada. *Apidologie* 36:623-633. doi:10.1051/apido:2005048
- Bailey L, Gibbs AJ (1964) Acute infection of bees with paralysis virus. *Journal of Insect Pathology* 6:395-407.
- Bailey S, Requier F, Nusillard B, Roberts SPM, Potts SG, Bouget C (2014) Distance from forest edge affects bee pollinators in oilseed rape fields. *Ecology and Evolution* 4:370-380. doi:10.1002/ece3.924
- Baker RA (2010) The parasitic mites of honey bees - past, present and future. *Journal of Entomological Research* 1:1-7.
- Bakonyi T, Grabensteiner E, Kolodziejek J, Rusvai M, Topolska G, Ritter W, Nowotny N (2002) Phylogenetic analysis of acute bee paralysis virus strains. *Applied and Environmental Microbiology* 68:6446-6450. doi:10.1128/Aem.68.12.6446-6450.2002
- Baldock KC, Goddard MA, Hicks DM, Kunin WE, Mitschunas N, Osgathorpe LM, Potts SG, Robertson KM, Scott AV, Stone GN, et al. (2015) Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects. *Proceedings of the Royal Society B: Biological Sciences* 282:20142849. doi:10.1098/rspb.2014.2849
- Baliddawa C (1985) Plant-species diversity and crop pest-control: an analytical review. *Insect Science and Its Application* 6:479-487.
- Ball BV, Bailey L (1997) Viruses. pp. 11-32 in *Honey Bee Pests, Predators, & Diseases*. Eds. Morse RA, Flottum K. A.I. Root Company, Medina, Ohio, USA.

- Banaszak-Cibicka W, Zmihorski M (2012) Wild bees along an urban gradient: winners and losers. *Journal of Insect Conservation* 16:331-343. doi:10.1007/s10841-011-9419-2
- Banaszak J, Dochkova B (2014) Bees (Hymenoptera, Apoidea, Apiformes) in the agricultural landscape of Bulgaria: species diversity. *Journal of Apicultural Science* 58:29-49. doi:10.2478/jas-2014-0003
- Banaszek J (1992) Strategy for conservation of wild bees in agricultural landscape. *Agriculture, Ecosystem & Environment* 40:179-192.
- Banda HJ, Paxton RJ (1991) Pollination of greenhouse tomatoes by bees. *Acta Horticulturae* (Wageningen) 288:194-198.
- Banks DJ, Pittman RN, Moffett JO (1985) Honey bees increase outcrossing in peanuts (*Arachis hypogaea* L). *American Journal of Botany* 72:875-875.
- Barber NA, Adler LS, Bernardo HL (2011) Effects of above- and belowground herbivory on growth, pollination, and reproduction in cucumber. *Oecologia* 165:377-386. doi:10.1007/s00442-010-1779-x
- Barbosa WF, De Meyer L, Guedes RNC, Smagghe G (2015) Lethal and sublethal effects of azadirachtin on the bumble bee *Bombus terrestris* (Hymenoptera: Apidae). *Ecotoxicology* 24:130-142. doi:10.1007/s10646-014-1365-9
- Baron GL, Raine NE, Brown MJF (2014) Impact of chronic exposure to a pyrethroid pesticide on bumblebees and interactions with a trypanosome parasite. *Journal of Applied Ecology* 51:460-469. doi:10.1111/1365-2664.12205
- Barthell JF, Frankie GW, Thorp RW (1998) Invader effects in a community of cavity nesting megachilid bees (Hymenoptera: Megachilidae). *Environmental Entomology* 27:240-247.
- Bartomeus I, Ascher JS, Wagner D, Danforth BN, Colla S, Kornbluth S, Winfree R (2011) Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences of the United States of America* 108:20645-20649. doi:10.1073/pnas.1115559108
- Bartomeus I, Park MG, Gibbs J, Danforth BN, Lakso AN, Winfree R (2013) Biodiversity ensures plant-pollinator phenological synchrony against climate change. *Ecology Letters* 16:1331-1338. doi:10.1111/ele.12170
- Bartomeus I, Potts SG, Steffan-Dewenter I, Vaissière BE, Woyciechowski M, Krewenka KM, Tscheulin T, Roberts SPM, Szentgyörgy H, Westphal C, Bommarco R (2014) Contribution of insect pollinators to crop yield and quality varies with agricultural intensification. *PeerJ* 2:e328. doi:10.7717/peerj.328
- Basualdo M, Del Hoyo ML, Bedascarrasbure EL (1998) Honeybee foraging activity in relation to flowering in oilseed rape. *Apiacta* 33:121-127.
- Batáry P, Báldi A, Saropataki M, Kohler F, Verhulst J, Knop E, Herzog F, Kleijn D (2010) Effect of conservation management on bees and insect-pollinated grassland plant communities in three European countries. *Agriculture, Ecosystems & Environment* 136:35-39. doi:10.1016/j.agee.2009.11.004
- Batáry P, Baldi A, Kleijn D, Tscharnkte T (2011) Landscape-moderated biodiversity effects of agri-environmental management: a meta-analysis. *Proceedings of the Royal Society B: Biological Sciences* 278:1894-1902.

- Batáry P, Dicks L, Kleijn D, Sutherland W (2015) The role of agri-environment schemes in conservation and environmental management. *Conservation Biology* 29:1006-1016. doi:10.1111/cobi.12536
- Bates AJ, Sadler JP, Fairbrass AJ, Falk SJ, Hale JD, Matthews TJ (2011) Changing bee and hoverfly pollinator assemblages along an urban-rural gradient. *PLoS One* 6:e23459. doi:10.1371/journal.pone.0023459
- Batra SWT (1981) Biological control in agroecosystems. *Science* 4529:134-139.
- BCMA (2012) Tracheal mites in honey bee colonies British Columbia. British Columbia Ministry of Agriculture. Vancouver, British Columbia, Canada. [http://www.agf.gov.bc.ca/apiculture/factsheets/219\\_hbtm.htm](http://www.agf.gov.bc.ca/apiculture/factsheets/219_hbtm.htm)
- Bedford FE, Whittaker RJ, Kerr JT (2012) Systemic range shift lags among a pollinator species assemblage following rapid climate change. *Botany* 90:587-597. doi:10.1139/b2012-052
- Belfrage K, Bjorklund J, Salomonsson L (2005) The effects of farm size and organic farming on diversity of birds, pollinators, and plants in a Swedish landscape. *Ambio* 34:582-588.
- Benachour K, Louadi K (2011) Foraging behavior of bees (Hymenoptera: Apoidea) on male and female flowers of cucumber (*Cucumis sativus* L.) (Cucurbitaceae) in Constantine area (Algeria). *Annales de La Societe Entomologique de France* 47:63-70.
- Bengtsson J, Ahnstrom J, Weibull A (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology* 42:261-269.
- Benjamin FE, Reilly JR, Winfree R (2014) Pollinator body size mediates the scale at which land use drives crop pollination services. *Journal of Applied Ecology* 51:440-449. doi:10.1111/1365-2664.12198
- Benjamin FE, Winfree R (2014) Lack of pollinators limits fruit production in commercial blueberry (*Vaccinium corymbosum*). *Environmental Entomology* 43:1574-1583. doi:10.1603/EN13314
- Beekman M, Ratnieks FLW (2000) Long-range foraging by the honey bee, *Apis mellifera* L. *Functional Ecology* 14:490-496. doi:10.1046/J.1365-2435.2000.00443.X
- Beil M, Kratochwil A, Storm C, Schwabe A (2014) Community structure and diversity of vegetation and flower-visiting wild bees (Hymenoptera: Apoidea) in sandy dry grassland: are there congruent characteristics? *Phytocoenologia* 44:175-192. doi:10.1127/0340-269x/2014/0044-0587
- Benelli G, Benvenuti S, Desneux N, Canale A (2014) *Cephalaria transsylvanica*-based flower strips as potential food source for bees during dry periods in European Mediterranean basin countries. *PLoS One* 9:e93153. doi:10.1371/journal.pone.0093153
- Benvenuti S (2014) Wildflower green roofs for urban landscaping, ecological sustainability and biodiversity. *Landscape and Urban Planning* 124:151-161. doi:10.1016/j.landurbplan.2014.01.004
- Berg CC (1989) Classification and distribution of *Ficus*. *Experientia* 45:605-611.
- Bjorkman T (1995) Role of honey bees (Hymenoptera, Apidae) in the pollination of buckwheat in eastern North America. *Journal of Economic Entomology* 88:1739-1745.

- Berthoud H, Imdorf A, Haueter M, Radloff S, Neumann P (2010) Virus infections and winter losses of honey bee colonies (*Apis mellifera*). *Journal of Apicultural Research* 49:60-65. doi:10.3896/ibra.1.49.1.08
- Bezemer TM, Harvey JA, Cronin JT (2014) Response of native insect communities to invasive plants. *Annual Review of Entomology* 59:119-141. doi:10.1146/Annurev-Ento-011613-162104
- Biddinger DJ, Robertson JL, Mullin C, Frazier J, Ashcraft SA, Rajotte EG, Joshi NK, Vaughn M (2013) Comparative toxicities and synergism of apple orchard pesticides to *Apis mellifera* (L.) and *Osmia cornifrons* (Radoszkowski). *PLoS One* 8:e72587. doi:10.1371/journal.pone.0072587
- Biesmeijer JC (2012) Causes of the decline of wild bees in North-West Europe. *Entomologische Berichten Amsterdam* 72:14-20.
- Biesmeijer JC, Roberts SPM, Reemer M, Ohlemueller R, Edwards M, Peeters T, Schaffers AP, Potts SG, Kleukers R, Thomas CD, et al. (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313:351-354. doi:10.1126/science.1127863
- Birmingham AL, Winston ML (2004) Orientation and drifting behaviour of bumblebees (Hymenoptera: Apidae) in commercial tomato greenhouses. *Canadian Journal of Zoology* 82:52-59. doi:10.1139/z03-201
- Blaauw BR, Isaacs R (2014a) Larger patches of diverse floral resources increase insect pollinator density, diversity, and their pollination of native wild flowers. *Basic and Applied Ecology* 15:701-711. doi:10.1016/j.baae.2014.10.001
- Blaauw BR, Isaacs R (2014b) Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *Journal of Applied Ecology* 51:890-898. doi:10.1111/1365-2664.12257
- Blacqui re T, Smagghe G, van Gestel CAM, Mommaerts V (2012) Neonicotinoids in bees: a review on concentrations, side-effects and risk assessment. *Ecotoxicology* 21:973-992. doi:10.1007/s10646-012-0863-x
- Blake R, Westbury D, Woodcock B, Sutton P, Potts S (2011a) Enhancing habitat to help the plight of the bumblebee. *Pest Management Science* 67:377-379. doi:10.1002/ps.2136
- Blake R, Woodcock B, Westbury D, Sutton P, Potts S (2011b) New tools to boost butterfly habitat quality in existing grass buffer strips. *Journal of Insect Conservation* 15:221-232. doi:10.1007/s10841-010-9339-6
- Blaschon B, Guttenberger H, Hrassnigg N, Crailsheim K (1999) Impact of bad weather on the development of the broodnest and pollen stores in a honeybee colony (Hymenoptera: Apidae). *Entomologia Generalis* 24:49-60.
- Blazyte-Cereskiene L, Buda V, Bagdonaite E (2012) Three wild Lithuanian strawberry species and their pollinators. *Plant Systematics and Evolution* 298:819-826. doi:10.1007/s00606-012-0593-9
- Bohart GE (1972) Management of wild bees for pollination of crops. *Annual Review of Entomology* 17:287-312.



- Boily M, Sarrasin B, DeBlois C, Aras P, Chagnon M (2013) Acetylcholinesterase in honey bees (*Apis mellifera*) exposed to neonicotinoids, atrazine and glyphosate: laboratory and field experiments. *Environmental Science and Pollution Research* 20:5603-5614. doi:10.1007/s11356-013-1568-2
- Bollan KA, Hothersall DJ, Moffat C, Durkacz J, Saranzewa N, Wright GA, Raine NE, Hight F, Connolly CN (2013). The microsporidian parasites *Nosema ceranae* and *Nosema apis* are widespread in honeybee (*Apis mellifera*) colonies across Scotland. *Parasitology Research* 112:751-759. doi:10.1007/s00436-012-3195-0
- Bommarco R, Biesmeijer JC, Meyer B, Potts SG, Poyry J, Roberts SPM, Steffan-Dewenter I, Ockinger E (2010) Dispersal capacity and diet breadth modify the response of wild bees to habitat loss. *Proceedings of the Royal Society B: Biological Sciences* 277:2075-2082. doi:10.1098/rspb.2009.2221
- Bommarco R, Marini L, Vaissière BE (2012) Insect pollination enhances seed yield, quality, and market value in oilseed rape. *Oecologia* 169:1025-1032. doi:10.1007/s00442-012-2271-6
- Bond WJ (1995) Assessing the risk of plant extinction due to pollinator disperser failure. pp. 122-128 in *Extinction Rates*. Eds. Lawton JG, May RM. Oxford University Press, Oxford, UK.
- Bosch J (1994) Improvement of field management of *Osmia cornuta* (Latreille) (Hymenoptera, Megachilidae) to pollinate almond. *Apidologie* 25:71-83.
- Bosch J, Kemp WP (1999) Exceptional cherry production in an orchard pollinated with blue orchard bees. *Bee World* 80:163-173.
- Bosch J, Kemp WP (2000) Development and emergence of the orchard pollinator *Osmia lignaria* (Hymenoptera: Megachilidae). *Environmental Entomology* 29:8-13. doi:10.1603/0046-225x-29.1.8
- Bosch J, Kemp WP (2001) *How to Manage the Blue Orchard Bee as an Orchard Pollinator*. Sustainable Agriculture Network, Beltsville, Maryland, USA.
- Bosch J, Kemp WP (2002) Developing and establishing bee species as crop pollinators: the example of *Osmia* spp. (Hymenoptera: Megachilidae) and fruit trees. *Bulletin of Entomological Research* 92:3-16.
- Bosch J, Kemp WP (2003) Effect of wintering duration and temperature on survival and emergence time in males of the orchard pollinator *Osmia lignaria* (Hymenoptera: Megachilidae). *Environmental Entomology* 32:711-716.
- Bosch J, Kemp WP, Trostle GE (2006) Bee population returns and cherry yields in an orchard pollinated with *Osmia lignaria* (Hymenoptera: Megachilidae). *Journal of Economic Entomology* 99:408-413.
- Bosch J, Sgolastra F, Kemp WP (2010) Timing of eclosion affects diapause development, fat body consumption and longevity in *Osmia lignaria*, a univoltine, adult-wintering solitary bee. *Journal of Insect Physiology* 56:1949-1957. doi:10.1016/j.jinsphys.2010.08.017
- Botías C, Martin-Hernandez R, Barrios L, Meana A, Higes M (2013) *Nosema* spp. infection and its negative effects on honey bees (*Apis mellifera iberiensis*) at the colony level. *Veterinary Research* 44:1-15. doi:10.1186/1297-9716-44-25 25

- Boutin C, Jobin B (1998) Intensity of agricultural practices and effects on adjacent habitats. *Ecological Applications* 8:544-557.
- Boutin C, Aya KL, Carpenter D, Thomas P, Rowland O (2012) Phytotoxicity testing for herbicide regulation: shortcomings in relation to biodiversity and ecosystem services in agrarian systems. *Science of the Total Environment* 415:79-92. doi:10.1016/j.scitotenv.2011.04.046
- Boyle RMD, Philogene BJR (1983) The native pollinators of an apple orchard – variations and significance. *Journal of Horticultural Science* 58:355-363.
- Breeze TD, Bailey AP, Balcombe KG, Potts SG (2011) Pollination services in the UK: how important are honeybees? *Agriculture, Ecosystems & Environment* 142:137-143. doi:10.1016/j.agee.2011.03.020
- Breeze TD, Bailey AP, Potts SG, Balcombe KG (2015) A stated preference valuation of the non-market benefits of pollination services in the UK. *Ecological Economics* 111:76-85. doi:10.1016/j.ecolecon.2014.12.022
- Brittain CA, Vighi M, Bommarco R, Settele J, Potts SG (2010) Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology* 11:106-115. doi:10.1016/j.baae.2009.11.007
- Brittain C, Kremen C, Klein A-M (2013a) Biodiversity buffers pollination from changes in environmental conditions. *Global Change Biology* 19:540-547. doi:10.1111/gcb.12043
- Brittain C, Williams N, Kremen C, Klein A-M (2013b) Synergistic effects of non-*Apis* bees and honey bees for pollination services. *Proceedings of the Royal Society B: Biological Sciences* 280:20122767. doi:10.1098/rspb.2012.2767
- Brookes B, Small E, Lefkovitch LP, Damman H, Faurey DT (1994) Attractiveness of alfalfa (*Medicago sativa* L) to wild pollinators in relation to wildflowers. *Canadian Journal of Plant Science* 74:779-783.
- Brosi BJ, Daily GC, Ehrlich PR (2007) Bee community shifts with landscape context in a tropical countryside. *Ecological Applications* 17:418-430. doi:10.1890/06-0029
- Brosi BJ, Armsworth PR, Daily GC (2008) Optimal design of agricultural landscapes for pollination services. *Conservation Letters* 1:27-36. doi:10.1111/j.1755-263X.2008.00004.x
- Broussard M, Rao S, Stephen WP, White L (2011) Native Bees, honeybees, and pollination in Oregon cranberries. *Hortscience* 46:885-888.
- Brown MJF, Paxton RJ (2009) The conservation of bees: a global perspective. *Apidologie* 40:410-416. doi:10.1051/apido/2009019
- Brown, MJF, Schmid-Hempel R, Schmid-Hempel P (2003) Strong context-dependent virulence in a host-parasite system: reconciling genetic evidence with theory. *Journal of Animal Ecology* 72:994-1002. doi:10.1046/j.1365-2656.2003.00770.x
- Brunet J, Stewart CM (2010) Impact of bee species and plant density of alfalfa pollination and potential for gene flow. *Psyche* 2010:201858. doi:10.1155/2010/201858
- Bryden J, Gill RJ, Mitton RAA, Raine NE, Jansen VAA (2013) Chronic sublethal stress causes bee colony failure. *Ecology Letters* 16:1463-1469. doi:10.1111/ele.12188

Burd M (1994) Bateman's principle and plant reproduction: the role of pollen limitation in fruit and seed set. *The Botanical Review* 60:83-139.

Buri P, Humbert JY, Arlettaz R (2014) Promoting pollinating insects in intensive agricultural matrices: field-scale experimental manipulation of hay-meadow mowing regimes and its effects on bees. *PLoS One* 9:e85635. doi:10.1371/journal.pone.0085635

Burkle LA, Alarcon R (2011) The future of plant-pollinator diversity: understanding interaction networks across time, space, and global change. *American Journal of Botany* 98:528-538. doi:10.3732/ajb.1000391

Burkle LA, Marlin JC, Knight TM (2013) Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function. *Science* 339:1611-1615. doi:10.1126/science.1232728

Cadotte MW, Carscadden K, Mirotchnick N (2011) Beyond species: functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology* 48:1079-1087. doi:10.1111/j.1365-2664.2011.02048.x

Cahill JF Jr, Elle E, Smith GR, Shore BH (2008) Disruption of a belowground mutualism alters interactions between plants and their floral visitors. *Ecology* 89:1791- 1801. doi:10.1890/07-0719.1

Calder A (1986) *Oilseed Rape and Bees*. Northern Bee Books, Hebden Bridge, UK.

Calderone NW (2012) Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992-2009. *PLoS One* 7:e37235. doi:10.1371/journal.pone.0037235

Calmasur O, Ozbek H (1999) Pollinator bees (Hymenoptera, Apoidea) on sunflower (*Helianthus annuus* L.) and their effects on seed setting in Erzurum region. *Turkish Journal of Biology* 23:73-89.

Calzoni GL, Speranza A (1996) Pear and plum pollination: honey bees, bumble bees of both? *Second Workshop on Pollination* 423:83-90.

Cameron SA, Lozier JD, Strange JP, Koch JB, Cordes N, Solter LF, Griswold TL (2011) Patterns of widespread decline in North American bumble bees. *Proceedings of the National Academy of Sciences of the United States of America* 108:662-667. doi:10.1073/pnas.1014743108

Cane JH (2001) Habitat fragmentation and native bees: a premature verdict? *Conservation Ecology* 5:3.

Cane JH (2002) Pollinating bees (Hymenoptera: Apiformes) of US alfalfa compared for rates of pod and seed set. *Journal of Economic Entomology* 95:22-27. doi:10.1603/0022-0493-95.1.22

Cane JH, Griswold T, Parker FD (2007) Substrates and materials used for nesting by North American *Osmia* bees (Hymenoptera: Apiformes: Megachilidae). *Annals of the Entomological Society of America* 100:350-358.

Cane JH (2008) A native ground-nesting bee (*Nomia melanderi*) sustainably managed to pollinate alfalfa across an intensively agricultural landscape. *Apidologie* 39:315-323. doi:10.1051/apido:2008013

- CAPA (1985) Chalkbrood in alfalfa leafcutting bees. Beaverlodge, Alberta.  
<http://capabees.org/content/uploads/2013/02/chalkbroodeafcutter.pdf>
- CAPA (1990) Canadian Association of Professional Apiculturists annual meeting proceedings, January 21-23 1990. Winnipeg, Manitoba.
- CAPA (1995) A guide to managing bees for crop pollination. Guelph, Ontario, Canada.  
<http://capabees.org/content/uploads/2012/10/CAPAcroppollination.pdf>
- CAPA (1999) Canadian Association of Professional Apiculturists annual meeting proceedings, February 20-22 1999. Victoria, British Columbia, Canada.
- CAPA (2000) Canadian Association of Professional Apiculturists annual meeting proceedings, February 2-3 2000. Saskatoon, Saskatchewan, Canada.
- CAPA (2002) Canadian Association of Professional Apiculturists annual meeting proceeding, January 30-31 2002. Banff, Alberta, Canada.
- CAPA (2006) Canadian Association of Professional Apiculturists annual meetings proceedings, January 25 2006. Quebec City, Quebec, Canada.
- CAPA (2015) Canadian Association of Professional Apiculturists statement on honey bee wintering losses in Canada (2015). <http://capabees.org/shared/2015/07/2015-CAPA-Statement-on-Colony-Losses-July-16-Final-16-30.pdf>
- Cariveau DP, Williams NM, Benjamin FE, Winfree R (2013) Response diversity to land use occurs but does not consistently stabilise ecosystem services provided by native pollinators. *Ecology Letters* 16:903-911. doi:10.1111/ele.12126
- Cariveau DP, Winfree R (2015) Causes of variation in wild bee responses to anthropogenic drivers. *Current Opinion in Insect Science* 10:104-109. doi:10.1016/j.cois.2015.05.004
- Carpenter SG, Cottam G (1982) Growth and reproduction of American ginseng (*Panax quinquefolius*) in Wisconsin, USA. *Canadian Journal of Botany* 60:2692-2696.
- Carper AL, Adler LS, Warren PS, Irwin RE (2014) Effects of suburbanization on forest bee communities. *Environmental Entomology* 43:253-262. doi:10.1603/en13078
- Carre G, Roche P, Chifflet R, Morison N, Bommarco R, Harrison-Cripps J, Krewenka K, Potts S, Roberts SPM, Rodet G, et al. (2009) Landscape context and habitat type as drivers of bee diversity in European annual crops. *Agriculture, Ecosystems & Environment* 133:40-47. doi:10.1016/j.agee.2009.05.001
- Carreck N, Williams I (1998) The economic value of bees in the UK. *Bee World* 79:115-123.
- Carreck NL, Williams IH (2002) Food for insect pollinators on farmland: insect visits to flowers of annual seed mixtures. *Journal of Insect Conservation* 6:13-23. doi:10.1023/A:1015764925536
- Carreck NL, Ball BV, Martin SJ (2010) Honey bee colony collapse and changes in viral prevalence associated with *Varroa destructor*. *Journal of Apicultural Research* 49:93-94. doi:10.3896/IBRA.1.49.1.13
- Carvalho LG, Veldtman R, Shenkute AG, Tesfay GB, Pirk CWW, Donaldson JS, Nicolson SW (2011) Natural and within-farmland biodiversity enhances crop productivity. *Ecology Letters* 14:251-259. doi:10.1111/j.1461-0248.2010.01579.x

- Carvalho LG, Seymour CL, Nicolson SW, Veldtman R (2012) Creating patches of native flowers facilitates crop pollination in large agricultural fields: mango as a case study. *Journal of Applied Ecology* 49:1373-1383. doi:10.1111/j.13652664.2012.02217.x
- Carvalho LG, Kunin WE, Keil P, Aguirre-Gutiérrez J, Ellis WN, Fox R, Groom Q, Hennekens S, van Landuyt W, Maes D, et al. (2013) Species richness declines and biotic homogenization have slowed down for NW-European pollinators and plants. *Ecology Letters* 16:1416-1417. doi:10.1111/ele.12121
- Carvell C, Roy DB, Smart SM, Pywell RF, Preston CD, Goulson D (2006) Declines in forage availability for bumblebees at a national scale. *Biological Conservation* 132:481-489. doi:10.1016/j.biocon.2006.05.008
- Carvell C, Meek WR, Pywell RF, Goulson D, Nowakowski M (2007) Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *Journal of Applied Ecology* 44:29-40. doi:10.1111/j.1365-2664.2006.01249.x
- Carvell C, Osborne JL, Bourke AFG, Freeman SN, Pywell R, Heard MS (2011) Bumble bee species' responses to a targeted conservation measure depend on landscape context and habitat quality. *Ecological Applications* 21:1760-1771.
- Carvell C, Bourke AFG, Osborne JL, Heard MS (2015) Effects of an agri-environment scheme on bumble bee reproduction at local and landscape scales. *Basic and Applied Ecology* 16: 519–530. doi:10.1016/j.baae.2015.05.006
- Casacci LP, Cerrato C, Barbero F, Bosso L, Ghidotti S, Paveto M, Pesce M, Plazio E, Panizza G, Balletto E, Viterbi R, Bonelli S (2015) Dispersal and connectivity effects at different altitudes in the *Euphydryas aurinia* complex. *Journal of Insect Conservation* 19:265-277. doi:10.1007/s10841-014-9715-8
- Castro SL (2001) Propolis: biological and pharmacological activities. Therapeutic uses of this bee-product. *Annual Review of Biomedical Sciences* 3:49-83.
- CFIA (2013) Honey bee producer guide to the national bee farm level biosecurity standard. pp. 3-81 in *Growing Forward*. Canadian Food Inspection Agency, Ottawa, Ontario, Canada.
- Chagnon M, Gingras J, DeOliveira D (1991) Honey bee (Hymenoptera, Apidae) foraging behavior on raspberry pollination. *Journal of Economic Entomology* 84:457-460.
- Chagnon M, Gingras J, DeOliveira D (1993) Complementary aspects of strawberry pollination by honey and indigenous bees (Hymenoptera). *Journal of Economic Entomology* 86:416-420.
- Chandler LD, Heilman MD (1982) Hymenoptera associated with sunflower in the lower Rio Grande valley of Texas with notes on relative abundance, visitation times and foraging. *Southwestern Entomologist* 7:170-173.
- Chiasson H, Vincent C, de Oliveira D (1997) Effect of an insect vacuum device on strawberry pollinators. *Seventh International Symposium on Pollination* 437:373-377.
- Chamberlain SA, Whitney KD, Rudgers JA (2013) Proximity to agriculture alters abundance and community composition of wild sunflower mutualists and antagonists. *Ecosphere* 4:96. doi:10.1890/es13-00026.1

- Chandrasekara LW, Pathiratne A (2007) Body size-related differences in the inhibition of brain acetylcholinesterase activity in juvenile Nile Tilapia (*Oreochromis niloticus*) by chlorpyrifos and carbosulfan. *Ecotoxicology and Environmental Safety* 67:109-119. doi:10.1016/J.Ecoenv.2006.04.002
- Chaplin-Kramer R, Tuxen-Bettman K, Kremen C (2011) Value of wildland habitat for supplying pollination services to Californian agriculture. *Rangelands* 33:33-41. doi:10.2111/1551-501X-33.3.33
- Chauzat MP, Martel AC, Zeggane S, Drajnudel P, Schurr F, Clement MC, Ribiere-Chabert M, Aubert M, Faucon JP (2010) A case control study and a survey on mortalities of honey bee colonies (*Apis mellifera*) in France during the winter of 2005-6. *Journal of Apicultural Research* 49:40-51. doi:10.3896/ibra.1.49.1.06
- Chen YP, Pettis JS, Corona M, Chen WP, Li CJ, Spivak M, Visscher PK, DeGrandi-Hoffman G, Boncristiani H, Zhao Y, et al. (2014) Israeli acute paralysis virus: epidemiology, pathogenesis and implications for honey bee health. *PLoS Pathogens* 10:e1004261. doi:10.1371/journal.ppat.1004261 e1004261
- Cobey S, Lawrence T (1986) More tracheal mites found in California. *American Bee Journal* 126:87-90.
- Colin ME, Belzunces LP (1992) Evidence of synergy between prochloraz and deltamethrin in *Apis mellifera* L. a convenient biological approach. *Pesticide Science* 36:115-119.
- Colla SR, Otterstatter MC, Gegear RJ, Thomson JD (2006) Plight of the bumble bee: pathogen spillover from commercial to wild populations. *Biological Conservation* 129:461-467. doi:10.1016/j.biocon.2005.11-.013
- Colla SR, Packer L (2008) Evidence for decline in eastern North American bumblebees (Hymenoptera: Apidae), with special focus on *Bombus affinis* Cresson. *Biodiversity and Conservation* 17:1379-13791. doi:10.1007/s10531-008-9340-5
- Colla S, Willis E, Packer L (2009) Can green roofs provide habitat for urban bees (Hymenoptera: Apidae)? *Cities and the Environment* 2:1-12.
- Colla SR, Gadallah F, Richardson L, Wagner D, Gall L (2012) Assessing declines of North American bumble bees (*Bombus* spp.) using museum specimens. *Biodiversity and Conservation* 21:3585-3595. doi:10.1007/s10531-012-0383-2
- Colla SR (2016) Status, threats and conservation recommendations for wild bumble bees (*Bombus* spp.) in Ontario, Canada: a review for policymakers and practitioners. *Natural Areas Journal* 36:412-426. doi:10.3375/043.036.0408
- Committee on the Status of Pollinators in North America (2007) *Status of Pollinators in North America*. The National Academic Press, Washington D.C., USA.
- Cook DC, Thomas MB, Cunningham SA, Anderson DL, De Barro PJ (2007) Predicting the economic impact of an invasive species on an ecosystem service. *Ecological Applications* 17:1832-1840. doi:10.1890/06-1632.1
- Copley TR, Chen H, Giovenazzo P, Houle E, Jabaji SH (2012) Prevalence and seasonality of *Nosema* species in Quebec honey bees. *The Canadian Entomologist* 144:577-588. doi:10.4039/tce.2012.46

- Corbet SA (2000) Conserving compartments in pollination webs. *Conservation Biology* 14:1229-1231.
- Coristine LE, Soroye P, Soares RN, Robillard C, Kerr JT (2016) Dispersal limitation, climate change, and practical tools for butterfly conservation in intensively used landscapes. *Natural Areas Journal* 36: 440-452. doi:10.3375/043.036.0410
- Coroian CO, Munoz I, Schluns EA, Paniti-Teleky OR, Erler S, Furdui EM, Marghitas LA, Dezmirean DS, Schluns H, De La Rua P, et al. (2014) Climate rather than geography separates two European honeybee subspecies. *Molecular Ecology* 23:2353-2361. doi:10.1111/mec.12731
- COSEWIC (2010) *COSEWIC Assessment and Status Report on the Rusty-patched Bumble Bee Bombus affinis in Canada*. Government of Canada, Ottawa, Ontario, Canada.
- Costanza R, d'Arge R, Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neil RV, Paruelo J, et al. (1997) The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.
- Coumou D, Rahmstorf S (2012) A decade of weather extremes. *Nature Climate Change* 2:491-496. doi:10.1038/Nclimate1452
- Couvillon MJ, Schürch R, Ratnieks FLW (2014a) Dancing bees communicate a foraging preference for rural lands in high-level agri-environment schemes. *Current Biology* 24:1212-1215. doi:10.1016/j.cub.2014.03.072
- Couvillon MJ, Schürch R, Ratnieks FLW (2014b) Waggle dance distances as integrative indicators of seasonal foraging challenges. *PLoS One* 9:e93495. doi:10.1371/journal.pone.0093495 e93495
- Couvillon MJ, Ratnieks FLW (2015) Environmental consultancy: dancing bee bioindicators to evaluate landscape "health". *Frontiers in Ecology and Evolution* 3:44 doi:10.3389/fevo.2015.00044
- Cox-Foster DL, Conlan S, Holmes EC, Palacios G, Evans JD, Moran NA, Quan PL, Briese T, Hornig M, Geiser DM, et al. (2007) A metagenomic survey of microbes in honey bee colony collapse disorder. *Science* 318:283-287. doi:10.1126/Science.1146498
- Cresswell JE, Page CJ, Uygun MB, Holmbergh M, Li Y, Wheeler JG, Laycock I, Pook CJ, Hempel de Ibarra N, Smirnoff N, Tyler CR (2012) Differential sensitivity of honey bees and bumble bees to a dietary insecticide (imidacloprid). *Zoology* 115:365-371. doi:10.1016/j.zool.2012.05.003
- Croxton PJ, Carvell C, Mountford JO, Sparks TH (2002) A comparison of green lanes and field margins as bumblebee habitat in an arable landscape. *Biological Conservation* 107:365-374. doi:10.1016/S0006-3207(02)00074-5
- Cunha R, Saraiva A, Cugnasca C, Hirakawa A, Imperatriz-Fonseca V (2001) WebBee: a web-based information system for research on stingless bees. *World Conference of Computers in Agriculture and Natural Resources* 77:676-682.
- Currie DJ, Mittelbach GG, Cornell HV, Field R, Guegan JF, Hawkins BA, Kaufman DM, Kerr JT, Oberdorff T, O'Brien E, et al. (2004) Predictions and tests of climate-based hypotheses of broad-scale variation in taxonomic richness. *Ecology Letters* 7:1121-1134. doi:10.1111/j.1461-0248.2004.00671.x

- Currie RW, Gatten P (2006) Timing acaricide treatments to prevent *Varroa destructor* (Acari: Varroidae) from causing economic damage to honey bee colonies. The Canadian Entomologist 138:238-252. doi:10.4039/n05-024
- Currie RW, Pernal SF, Guzmán-Novoa E (2010) Honey bee colony losses in Canada. Journal of Apicultural Research 49:104-106. doi:10.3896/ibra.1.49.1.18
- Cusser S, Goodell K (2013) Diversity and distribution of floral resources influence the restoration of plant-pollinator networks on a reclaimed strip mine. Restoration Ecology 21:713-721. doi:10.1111/rec.12003
- Cuthbertson AGS, Wakefield ME, Powell ME, Marris G, Anderson H, Budge GE, Mathers JJ, Blackburn LF, Brown MA (2013) The small hive beetle *Aethina tumida*: a review of its biology and control measures. Current Zoology 59:644-653.
- Cutler GC, Scott-Dupree CD (2007) Exposure to clothianidin seed-treated canola has no long-term impact on honey bees. Journal of Economic Entomology 100:765-772. doi:10.1603/0022-0493(2007)100[765:etcsch]2.0.co;2
- Cutler GC, Reeh KW, Sproule JM, Ramanaidu K (2012) Berry unexpected: nocturnal pollination of lowbush blueberry. Canadian Journal of Plant Science 92:707-711. doi:10.4141/cjps2012-026
- Cutler GC, Scott-Dupree CD, Drexler DM (2014a) Honey bees, neonicotinoids and bee incident reports: the Canadian situation. Pest Management Science 70:779-783. doi:10.1002/ps.3613
- Cutler GC, Scott-Dupree CD, Sultan M, McFarlane AD, Brewer L (2014b) A large-scale field study examining effects of exposure to clothianidin seed-treated canola on honey bee colony health, development, and overwintering success. PeerJ 2:e652. doi:10.7717/peerj.652
- Cutler GC, Nams VO, Craig P, Sproule JM, Sheffield CS (2015) Wild bee pollinator communities of lowbush blueberry fields: Spatial and temporal trends. Basic and Applied Ecology 16:73-85. doi:10.1016/j.baae.2014.11.005
- Dainat B, Evans JD, Chen YP, Gauthier L, Neumann P (2012) Predictive markers of honey bee colony collapse. PLoS One 7:e32151. doi:10.1371/journal.pone.0032151
- Dag A, Eisikowitch D (1995) The influence of hive location on honeybee foraging activity and fruit set in melons grown in plastic greenhouses. Apidologie 26:511-519. doi:10.1051/apido:19950608
- Dag A, Kammer Y (2001) Comparison between the effectiveness of honey bee (*Apis mellifera*) and bumble bee (*Bombus terrestris*) as pollinators of greenhouse sweet pepper (*Capsicum annuum*). American Bee Journal 141:447-448.
- Danka RG, Villa JD (2003) Autogrooming by resistant honey bees challenged with individual tracheal mites. Apidologie 34:591-596. doi:10.1051/Apido:2003050
- Danka RG, de Guzman LI, Rinderer TE, Sylvester HA, Wagener CM, Bourgeois AL, Harris JW, Villa JD (2012) Functionality of *Varroa*-resistant honey bees (Hymenoptera: Apidae) when used in migratory beekeeping for crop pollination. Journal of Economic Entomology 105:313-321.



- Darvill B, O'Connor S, Lye GC, Waters J, Lepais O, Goulson D (2010) Cryptic differences in dispersal lead to differential sensitivity to habitat fragmentation in two bumblebee species. *Molecular Ecology* 19:53-63. doi:10.1111/j.1365-294X.2009.04423.x
- David A, Botías C, Abdul-Sada A, Nicholls E, Rotheray EL, Hill EM, Goulson D (2016). Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. *Environment International* 88:169-178. doi:10.1016/j.envint.2015.12.011
- Davila YC, Elle E, Vamosi JC, Hermanutz L, Kerr JT, Lortie CJ, Westwood AR, Woodcock TS, Worley AC (2012) Ecosystem services of pollinator diversity: a review of the relationship with pollen limitation of plant reproduction. *Botany* 90:535-543. doi:10.1139/b2012-017
- Davis AR, Solomon KR, Shuel RW (1988) Laboratory studies of honeybee larval growth and development as affected by systemic insecticides at adult-sublethal levels. *Journal of Apicultural Research* 27:146-161.
- de Guzman LI, Frake AM, Rinderer TE (2010) Seasonal population dynamics of small hive beetles, *Aethina tumida* Murray, in the south-eastern USA. *Journal of Apicultural Research* 49:186-191. doi:10.3896/ibra.1.49.2.07
- De Jong D, Morse RA, Eickwort GC (1982) Mite pests of honey bees. *Annual Review of Entomology* 27:229-252.
- De Jong D, da Silva EJ, Kevan PG, Atkinson JL (2009) Pollen substitutes increase honey bee haemolymph protein levels as much as or more than does pollen. *Journal of Apicultural Research* 48:34-37. doi:10.3896/Ibra.1.48.1.08
- De la Rúa P, Serrano J, Galian J (2002) Biodiversity of *Apis mellifera* populations from Tenerife (Canary Islands) and hybridisation with east European races. *Biodiversity Conservation* 11:59-67. doi:10.1023/A:1014066407307
- De la Rúa P, Jaffe R, Dall O, Raffaele, Munoz I, Serrano J (2009) Biodiversity, conservation and current threats to European honeybees. *Apidologie* 40:263-284. doi:10.1051/apido/2009027
- De la Rúa P, Jaffe R, Munoz I, Serrano J, Moritz RFA, Kraus FB (2013) Conserving genetic diversity in the honeybee: comments on Harpur et al. (2012). *Molecular Ecology* 22:3208-3210. doi:10.1111/Mec.12333
- de Miranda JR, Cordoni G, Budge G (2010) The acute bee paralysis virus–Kashmir bee virus–Israeli acute paralysis virus complex. *Journal of Invertebrate Pathology* 103:S30-S47. doi:10.1016/j.jip.2009.06.014
- de Snoo G, Van der Poll RJ (1989) Effect of herbicide drift on adjacent boundary vegetation. *Agriculture, Ecosystems & Environment* 73:1-6.
- de Snoo GR, Herzon I, Staats H, Burton RJF, Schindler S, van Dijk J, Lokhorst AM, Bullock JM, Lobley M, Wrba T, et al. (2013) Toward effective nature conservation on farmland: making farmers matter. *Conservation Letters* 6:66-72. doi:10.1111/j.1755-263X.2012.00296.x
- DEFRA (2005) *Environmental Stewardship: Entry Level Stewardship Handbook*. Natural England, London, UK.

DEFRA (2013) *Environmental Stewardship: Higher Level Stewardship Handbook*. Natural England, London, UK.

Degrandi GL, Collison CH (1980) Factors affecting honey bee *Apis mellifera* L. (Hymenoptera, Apidae) – foraging on birdsfoot-trefoil (*Lotus corniculatus*). Journal of the New York Entomological Society 88:43-43.

Delaplane K, Mayer D (2000) *Crop Pollination by Bees*. CABI Publishing, New York, New York, USA.

Delaplane KS, Ellis JD, Hood VM (2010) A test for interactions between *Varroa destructor* (Acari: Varroidae) and *Aethina tumida* (Coleoptera: Nitidulidae) in colonies of honey bees (Hymenoptera: Apidae). Annals of the Entomological Society of America 103:711-715. doi:10.1603/AN09169

Delfinado-Baker M (1988) The tracheal mite of honey-bees: a crisis in beekeeping. pp. 493-497 in *Africanized honey bees and bee mites*. Ed. Needham GR. Ellis Horwood Ltd, Chichester, England, UK.

Desai SD, Kumar S, Currie RW (2016) Occurrence, detection and quantification, of economically important viruses in healthy and unhealthy honey bee (Hymenoptera: Apidae) colonies in Canada. The Canadian Entomologist 148:22-35. doi:10.4039/tce.2015.23

Deseyn J, Billen J (2005) Age-dependent morphology and ultra-structure of the hypopharyngeal gland of *Apis mellifera* workers (Hymenoptera, Apidae). Apidologie 36:49-57. doi:10.1051/apido:2004068

Desneux N, Decourtye A, Delpuech JM (2007) The sublethal effects of pesticides on beneficial arthropods. Annual Review of Entomology 52:81-106. doi:10.1146/annurev.ento.52.110405.091440

Devictor V, Julliard R, Couvet D, Jiguet F (2008) Birds are tracking climate warming, but not fast enough. Proceedings of the Royal Society B: Biological Sciences 275:2743-2748. doi:10.1098/rspb.2008.0878

Di Pasquale G, Salignon M, Le Conte Y, Belzunces LP, Decourtye A, Kretzschmar A, Suchail S, Brunet JL, Alaux C (2013) Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter? PLoS One 8:e72016. doi:10.1371/journal.pone.0072016

Dicks LV (2013) Bees, lies and evidence-based policy. Nature 494:283-283. doi:10.1038/494283a

Dicks LV, Abrahams A, Atkinson J, Biesmeijer J, Bourn N, Brown C, Brown MJF, Carvell C, Connolly C, Cresswell JE, et al. (2013) Identifying key knowledge needs for evidence-based conservation of wild insect pollinators: a collaborative cross-sectoral exercise. Insect Conservation and Diversity 6:435-446. doi:10.1111/j.1752-4598.2012.00221.x

Dicks LV, Baude M, Roberts SPM, Phillips J, Green M, Carvell C (2015) How much flower-rich habitat is enough for wild pollinators? Answering a key policy question with incomplete knowledge. Ecological Entomology 40:22-35. doi:10.1111/een.12226

Dicks LV, Viana B, Bommarco R, Brosi B, Arizmendi MdC, Cunningham SA, Galetto L, Hill R, Lopes AV, Pires C et al. (2016). Ten policies for pollinators. Science 354:975-976. doi:10.1126/science.aai9226

Dittmar PJ, Monks DW, Schultheis JR (2010) Use of commercially available pollenizers for optimizing triploid watermelon production. *Hortscience* 45:541-545.

Dixo M, Metzger JP, Morgante JS, Zamudio KR (2009) Habitat fragmentation reduces genetic diversity and connectivity among toad populations in the Brazilian Atlantic coastal forest. *Biological Conservation* 142:1560-1569.  
doi:10.1016/J.Biocon.2008.11.016

Dixon KW (2009) Pollination and restoration. *Science* 325:571-573.  
doi:10.1126/science.1176295

Dogterom MH, Matteoni JA, Plowright RC (1998) Pollination of greenhouse tomatoes by the North American *Bombus vosnesenskii* (Hymenoptera: Apidae). *Journal of Economic Entomology* 91:71-75.

Donkersley P, Rhodes G, Pickup RW, Jones KC, Wilson K (2014) Honeybee nutrition is linked to landscape composition. *Ecology and Evolution* 4:4195-4206.  
doi:10.1002/ece3.1293

Dormann CF, Schweiger O, Augenstein I, Bailey D, Billeter R, de Blust G, DeFilippi R, Frenzel M, Hendrickx F, Herzog F, et al. (2007) Effects of landscape structure and land-use intensity on similarity of plant and animal communities. *Global Ecology and Biogeography* 16:774-787. doi:10.1111/j.1466-8238.2007.00344.x

Doublet V, Labrussias M, de Miranda JR, Moritz RFA, Paxton RJ (2014) Bees under stress: sublethal doses of a neonicotinoid pesticide and pathogens interact to elevate honey bee mortality across the life cycle. *Environmental Microbiology* 17:969-983.  
doi:10.1111/1462-2920.12426.

Dover J, Sotherton N, Gobbett K (1990) Reduced pesticide inputs on cereal field margins: the effects on butterfly abundance. *Ecological Entomology* 15:17-24.

Downey DL, Higo TT, Winston ML (2000) Single and dual parasitic mite infestations on the honey bee, *Apis mellifera* L. *Insectes Sociaux* 47:171-176. doi:10.1007/pl00001697

Drummond F, Stubbs C (1997) Potential for management of the blueberry bee, *Osmia atriventris* Cresson. *Acta Horticulturae* 446:77-85.

Dupont YL, Hansen DM, Valido A, Olesen JM (2004) Impact of introduced honey bees on native pollination interactions of the endemic *Echium wildpreti* (Boraginaceae) on Tenerife, Canary Islands. *Biological Conservation* 118:301-311.  
doi:10.1016/j.biocon.2003.09.010

Dupont YL, Damgaard C, Simonsen V (2011) Quantitative historical change in bumblebee (*Bombus* spp.) assemblages of red clover fields. *PLoS One* 6:e25172.  
doi:10.1371/journal.pone.0025172

Durrer S, Schmid-Hempel P (1994) Shared use of flowers leads to horizontal pathogen transmission. *Proceedings of the Royal Society B: Biological Sciences* 258:299-302.

Dussaubat C, Maisonnasse A, Alaux C, Tchamitchan S, Brunet J-L, Plettner E, Belzunces LP, Le Conte Y (2010) *Nosema* spp. infection alters pheromone production in honey bees (*Apis mellifera*). *Journal of Chemical Ecology* 36:522-525. doi:10.1007/s10886-010-9786-2

Dussaubat C, Maisonnasse A, Crauser D, Beslay D, Costagliola G, Soubeyrand S, Kretzchmar A, Le Conte Y (2013) Flight behavior and pheromone changes associated to

- Nosema ceranae* infection of honey bee workers (*Apis mellifera*) in field conditions. *Journal of Invertebrate Pathology* 113:42-51. doi:10.1016/j.jip.2013.01.002
- Dylewska M, Jablonski B, Sowa S, Bilinski M, Wrona S (1970) An attempt of determination of the number of bees (Hymenoptera, Apoidea) needed for adequate pollination of alfalfa. *Polish Journal of Entomology* 40:371-398.
- Ebeling A, Klein A-M, Schumacher J, Weisser WW, Tscharntke T (2008) How does plant richness affect pollinator richness and temporal stability of flower visits? *Oikos* 117:1808-1815. doi:10.1111/j.1600-0706.2008.16819.x
- Eckert J (1942) The pollen required by a colony of honey bees. *Journal of Economic Entomology* 35:309-311.
- Eickwort GC, Ginsberg H (1980) Foraging and mating behaviour in Apoidea. *Annual Review of Entomology* 25:421-426.
- Eischen FA (1987) Overwintering performance of honey bee colonies heavily infested with *Acarapis woodi* (Rennie). *Apidologie* 18:293-304. doi:10.1051/apido:19870401
- Eischen FA, Cardosotamez D, Wilson WT, Dietz A (1989) Honey production of honey bee colonies infested with *Acarapsis woodi* (Rennie). *Apidologie* 20:1-8. doi:10.1051/apido:19890101
- Ekroos J, Piha M, Tiainen J (2008) Role of organic and conventional field boundaries on boreal bumblebees and butterflies. *Agriculture, Ecosystems & Environment* 124:155-159. doi:10.1016/j.agee.2007.09.003
- Elle E, Elwell S, Gielens G (2012) The use of pollination networks in conservation. *Botany-Botanique* 90:525-534.
- Ellis AM, Hayes GW (2009) Assessing the efficacy of a product containing *Bacillus thuringiensis* applied to honey bee (Hymenoptera: Apidae) foundation as a control for *Galleria mellonella* (Lepidoptera: Pyralidae). *Journal of Entomological Science* 44:158-163.
- Ellis C, Park KJ, Whitehorn P, David A, Goulson D (2017). The neonicotinoid insecticide thiacloprid impacts upon bumblebee colony development under field conditions. *Environmental Science & Technology* 51:1727–1732. doi:10.1021/acs.est.1026b04791.
- Ellis JD, Hepburn R, Delaplane KS, Neumann P, Elzen PJ (2003) The effects of adult small hive beetles, *Aethina tumida* (Coleoptera: Nitidulidae), on nests and flight activity of Cape and European honey bees (*Apis mellifera*). *Apidologie* 34:399-408. doi:10.1051/apido:2003038
- Ellis JD, Graham JR, Mortensen A (2013) Standard methods for wax moth research. *Journal of Apicultural Research* 52:1-18. doi:10.3896/Ibra.1.52.1.10
- Elston C, Thompson HM, Walters KFA (2013) Sub-lethal effects of thiamethoxam, a neonicotinoid pesticide, and propiconazole, a DMI fungicide, on colony initiation in bumblebee (*Bombus terrestris*) micro-colonies. *Apidologie* 44:563-574. doi:10.1007/s13592-013-0206-9

- Emsen B, Petukhova T, Guzman-Novoa E (2012) Factors limiting the growth of *Varroa destructor* populations in selected honey bee (*Apis mellifera* L.) colonies. *Journal of Animal and Veterinary Advances* 11:4519-4525.
- Emsen B, Hamiduzzaman MM, Goodwin PH, Guzman-Novoa E (2015) Lower virus infections in *Varroa destructor*-infested and uninfested brood and adult honey bees (*Apis mellifera*) of a low mite population growth colony compared to a high mite population growth colony. *PLoS One* 10:e0118885. doi:10.1371/journal.pone.0118885
- European Court of Auditors (2011) Is agri-environment support well designed and managed? pp. 1-100 in *European Court of Auditors Specialist Report*. Publications Office of the European Union, Luxembourg. doi:10.2865/41418
- Evans EC, Spivak M (2006) Effects of honey bee (Hymenoptera: Apidae) and bumble bee (Hymenoptera: Apidae) presence on cranberry (Ericales: Ericaceae) pollination. *Journal of Economic Entomology* 99:614-620. doi:10.1603/0022-0493-99.3.
- Exeler N, Kratochwil A, Hochkirch A (2009) Restoration of riverine inland sand dune complexes: implications for the conservation of wild bees. *Journal of Applied Ecology* 46:1097-1105. doi:10.1111/j.1365-2664.2009.01701.x
- Exley C, Rotheray E, Goulson D (2015). Bumblebee pupae contain high levels of aluminium. *PLoS One* 10:e0127665. doi: 10.1371/journal.pone.0127665
- Eyer M, Chen YP, Schaefer MO, Pettis J, Neumann P (2009) Small hive beetle, *Aethina tumida*, as a potential biological vector of honeybee viruses. *Apidologie* 40:419-28. doi:10.1051/apido:2008051
- Fahrig L, Girard J, Duro D, Pasher J, Smith A, Javorek S, King D, Lindsay KF, Mitchell S, Tischendorf L (2015) Farmlands with smaller crop fields have higher within-field biodiversity. *Agriculture, Ecosystems & Environment* 200:219-234. doi:10.1016/j.agee.2014.11.018
- Farjan M, Dmitryjuk M, Lipinski Z, Biernat-Lopienska E, Zoltowska K (2012) Supplementation of the honey bee diet with vitamin C: the effect on the antioxidative system of *Apis mellifera carnica* brood at different stages. *Journal of Apicultural Research* 51:263-270. doi:10.3896/ibra.1.51.3.07
- Fausser-Misslin A, Sadd BM, Neumann P, Sandrock C (2014) Influence of combined pesticide and parasite exposure on bumblebee colony traits in the laboratory. *Journal of Applied Ecology* 51:450-459. doi:10.1111/1365-2664.12188
- Feber R, Firbank L, Johnson P, Macdonald D (1997) The effects of organic farming on pest and non-pest butterfly abundance. *Agriculture, Ecosystems & Environment* 64:133-139.
- FERA (2013) Effects of neonicotinoid seed treatments on bumble bee colonies under field conditions. The Food and Environment Research Agency, Sand Hutton, York, UK. <http://fera.co.uk/ccss/documents/defraBumbleBeeReportPS2371V4a.pdf>
- Feltham H, Park K, Goulson D (2014) Field realistic doses of pesticide imidacloprid reduce bumblebee pollen foraging efficiency. *Ecotoxicology* 23:317-323. doi:10.1007/s10646-014-1189-7.
- Fernandez JM, Puerta F, Cousinou M, Dios-Palomares R, Campano F, Redondo L (2012) Asymptomatic presence of *Nosema* spp. in Spanish commercial apiaries. *Journal of Invertebrate Pathology* 111:106-110. doi:10.1016/J.jip.2012.06.008

- Fetridge ED, Ascher JS, Langellotto GA (2008) The bee fauna of residential gardens in a suburb of New York city (Hymenoptera: Apoidea). *Annals of the Entomological Society of America* 101:1067-1077. doi:10.1603/0013-8746-101.6.1067
- Fiedler A, Landis D, Arduser M (2012) Rapid shift in pollinator communities following invasive species removal. *Restoration Ecology* 20:593-602. doi:10.1111/j.1526-100X.2011.00820.x
- Fliszkiewicz M, Giejdasz K, Wilkaniec Z (2011) The importance of male red mason bee (*Osmia rufa* L.) and male bufftailed bumblebee (*Bombus terrestris* L.) pollination in blackcurrant (*Ribes nigrum* L.). *Journal of Horticultural Science & Biotechnology* 86:457-460. doi:10.1080/14620316.2011.11512788
- Flores JM, Ruiz JA, Ruz JM, Puerta F, Bustos M, Padilla F, Campano F (1996) Effect of temperature and humidity of sealed brood on chalkbrood development under controlled conditions. *Apidologie* 27:185-192. doi:10.1051/apido:19960401
- Flores JM, Gutierrez I, Espejo R (2005) The role of pollen in chalkbrood disease in *Apis mellifera*: transmission and predisposing conditions. *Mycologia* 97:1171-6. doi:10.3852/mycologia.97.6.1171
- Fontaine C, Dajoz I, Meriguet J, Loreau M (2006) Functional diversity of plant-pollinator interaction webs enhances the persistence of plant communities. *PLoS Biology* 4:e1. doi:10.1371/journal.pbio.0040001
- Forbes I, Leuck DB, Edwardson JR, Burns RE (1971) Natural cross-pollination in blue lupine (*Lupinus angustifolius* L) in Georgia and Florida. *Crop Science* 11:851-854.
- Forister ML, Cousens B, Harrison JG, Anderson K, Thorne JH, Waetjen D, Nice CC, De Parisa M, Hladik ML, Meese R, van Vliet H, Shapiro AM (2016). Increasing neonicotinoid use and the declining butterfly fauna of lowland California. *Biology Letters* 12: 20160475. doi:10.1098/rsbl.2016.0475
- Forrest JRK, Miller-Rushing AJ (2010) Toward a synthetic understanding of the role of phenology in ecology and evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365:3101-3112. doi:10.1098/rstb.2010.0145
- Forrest JRK, Thomson JD (2011) An examination of synchrony between insect emergence and flowering in Rocky Mountain meadows. *Ecological Monographs* 81:469-491. doi:10.1890/10-1885.1
- Forsgren E, Fries I (2010) Comparative virulence of *Nosema ceranae* and *Nosema apis* in individual European honey bees. *Veterinary Parasitology* 170:212-217. doi:10.1016/J.Vetpar.2010.02.010
- Forsgren E, Fries I (2013) Temporal study of *Nosema* spp. in a cold climate. *Environmental Microbiology Reports* 5:78-82. doi:10.1111/j.1758-2229.2012.00386.x
- Fortel L, Henry M, Guilbaud L, Guirao AL, Kuhlmann M, Mouret H, Rollin O, Vaissière BE (2014) Decreasing abundance, increasing diversity and changing structure of the wild bee community (Hymenoptera: Anthophila) along an urbanization gradient. *PLoS One* 9:e104679. doi:10.1371/journal.pone.0104679
- Forup ML, Memmott J (2005) The relationship between the abundances of bumblebees and honeybees in a native habitat. *Ecological Entomology* 30:47-57. doi:10.1111/j.0307-6946.2005.00660.x

- Francis RM, Nielsen SL, Kryger P (2013) *Varroa*-virus interaction in collapsing honey bee colonies. PLoS One 8:e57540. doi:10.1371/journal.pone.0057540
- Franzen M, Ockinger E (2012) Climate-driven changes in pollinator assemblages during the last 60 years in an Arctic mountain region in northern Scandinavia. Journal of Insect Conservation 16:227-238. doi:10.1007/s10841-011-9410-y
- Free JB (1966a) Pollinating efficiency of honey bee visits to apple flowers. Journal of Horticultural Science & Biotechnology 41:91-94.
- Free JB (1966b) The pollination of the beans *Phaseolus multiflorus* and *Phaseolus vulgaris* by honeybees. Journal of Apicultural Research 5:87-91.
- Free JB (1993) *Insect Pollination of Crops*. Academic Press, London, UK.
- Fronk D, Slater JA (1956) Insect fauna of cucurbit flowers. Journal of the Kansas Entomological Society 29:141-145.
- Frost EH, Shutler D, Hillier NK (2013) Effects of fluvalinate on honey bee learning, memory, responsiveness to sucrose, and survival. Journal of Experimental Biology 216:2931-2938. doi:10.1242/jeb.08658
- Frey E, Schnell H, Rosenkranz P (2011) Invasion of *Varroa destructor* mites into mite-free honey bee colonies under the controlled conditions of a military training area. Journal of Apicultural Research 50:138-144. doi:10.3896/ibra.1.50.2.05
- Frier D, Somers CM, Sheffield CS (2016) Comparing the performance of native and managed pollinators of Haskap (*Lonicera caerulea*: Caprifoliaceae), an emerging fruit crop. Agriculture, Ecosystems & Environment 219:42-48. doi:10.1016/j.agee.2015.12.011
- Fries I, Ekbohm G, Villumstad E (1984) *Nosema apis*, sampling techniques and honey yield. Journal of Apicultural Research 23:102-105.
- Fuchs S (1990) Preference for drone brood cells by *Varroa jacobsoni* Oud in colonies of *Apis mellifera carnica*. Apidologie 21:193-199. doi:10.1051/apido:19900304
- Fürst MA, McMahon DP, Osborne JL, Paxton RJ, Brown MJF (2014) Disease associations between honeybees and bumblebees as a threat to wild pollinators. Nature 506:364-366. doi:10.1038/Nature12977
- Gajc-Wolska J, Kowalczyk K, Mikas J, Drajski R (2011) Efficiency of cucumber (*Cucumis sativus* L.) pollination by bumblebees (*Bombus terrestris*). Acta Scientiarum Polonorum-Hortorum Cultus 10:159-169.
- Gallai N, Salles J-M, Settele J, Vaissière BE (2009) Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics 68:810-821. doi:10.1016/j.ecolecon.2008.06.014
- Garbian Y, Maori E, Kalev H, Shafir S, Sela I (2012) Bidirectional transfer of RNAi between honey bee and *Varroa destructor*: *Varroa* gene silencing reduces *Varroa* population. PLoS Pathogens 8:e1003035. doi:10.1371/journal.ppat.1003035
- Garcia RR, Miñarro M (2014) Role of floral resources in the conservation of pollinator communities in cider-apple orchards. Agriculture, Ecosystems & Environment 183:118-126. doi:10.1016/j.agee.2013.10.017

- Gardner KE, Ascher JS (2006) Notes on the native bee pollinators in New York apple orchards. *Journal of the New York Entomological Society* 114:86-91. doi:10.1664/0028-7199(2006)114[86:notnbp]2.0.co;2
- Garibaldi LA, Steffan-Dewenter I, Kremen C, Morales JM, Bommarco R, Cunningham SA, Carvalheiro LG, Chacoff NP, Dudenhoefter JH, Greenleaf SS, et al. (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits. *Ecology Letters* 14:1062-1072. doi:10.1111/j.1461-0248.2011.01669.x
- Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C, Carvalheiro LG, Harder LD, Afik O, et al. (2013) Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science* 339:1608-1611. doi:10.1126/science.1230200
- Garibaldi LA, Carvalheiro LG, Leonhardt SD, Aizen MA, Blaauw BR, Isaacs R, Kuhlmann M, Kleijn D, Klein A-M, Kremen C et al. (2014) From research to action: enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment* 12:439-447. doi:10.1890/130330
- Garratt MPD, Coston DJ, Truslove CL, Lappage MG, Polce C, Dean R, Beismeyer JC, Potts SG (2014) The identity of crop pollinators helps target conservation for improved ecosystem services. *Biological Conservation* 169:128-135. doi:10.1016/j.biocon.2013.11.001
- Gary NE, Page RE (1989) Tracheal mite (Acari, Tarsonemidae) infestation effects on foraging and survivorship of honey bees (Hymenoptera, Apidae). *Journal of Economic Entomology* 82:734-739.
- Gashout HA, Guzman-Novoa E (2009) Acute toxicity of essential oils and other natural compounds to the parasitic mite, *Varroa destructor*, and to larval and adult worker honey bees (*Apis mellifera* L.). *Journal of Apicultural Research* 48:263-269. doi:10.3896/ibra.1.48.4.06
- Gaston K, Smith R, Thompson K, Warren P (2005) Urban domestic gardens (II): experimental tests of methods for increasing biodiversity. *Biodiversity and Conservation* 14:395-413.
- Gathmann A, Tschardt T (2002) Foraging ranges of solitary bees. *Journal of Animal Ecology* 71:757-764. doi:10.1046/j.1365-2656.2002.00641.x
- Ghazoul J (2005a) Buzziness as usual? Questioning the global pollination crisis. *Trends in Ecology & Evolution* 20:367-373. doi:10.1016/j.tree.2005.04.026
- Ghazoul J (2005b) Pollen and seed dispersal among dispersed plants. *Biological Reviews* 80:413-443. doi:10.1017/S1464793105006731
- Genersch E (2010) American Foulbrood in honeybees and its causative agent, *Paenibacillus larvae*. *Journal of Invertebrate Pathobiology* 103:S10-S19. doi:10.1016/j.jip.2009.06.015
- Genersch E, Aubert M (2010) Emerging and re-emerging viruses of the honey bee (*Apis mellifera* L.). *Veterinary Research* 41:54. doi:10.1051/vetres/2010027
- Geslin B, Gauzens B, Thebault E, Dajoz I (2013) Plant pollinator networks along a gradient of urbanisation. *PLoS One* 8:e63421. doi:10.1371/journal.pone.0063421



- Ghisalberti EL (1979) Propolis: a review. *Bee World* 60:59-84.
- Gibbs J (2010) Revision of the metallic species of *Lasioglossum* (*Dialictus*) in Canada (Hymenoptera, Halictidae, Halictini). *Zootaxa* 2591:1-382.
- Gibson RH, Nelson IL, Hopkins GW, Hamlett BJ, Memmott J (2006) Pollinator webs, plant communities and the conservation of rare plants: arable weeds as a case study. *Journal of Applied Ecology* 43:246-257. doi:10.1111/j.1365-2664.2006.01130.x
- Gill KA, O'Neal ME (2015) Survey of soybean insect pollinators: community identification and sampling method analysis. *Environmental Entomology*, doi:10.1093/ee/nvv1001.
- Gill RJ, Raine NE (2014) Chronic impairment of bumblebee natural foraging behaviour induced by sublethal pesticide exposure. *Functional Ecology* 28:1459-1471. doi:10.1111/1365-2435.12292
- Gill RJ, Ramos-Rodriguez O, Raine NE (2012) Combined pesticide exposure severely affects individual- and colony-level traits in bees. *Nature* 491:105-108. doi:10.1038/nature11585
- Gilpin M (1991) The genetic effective size of a metapopulation. *Biological Journal of the Linnean Society* 42:165-175.
- Gingras D, Gingras J, De Oliveira D (1999) Visits of honeybees (Hymenoptera:Apidae) and their effects on cucumber yields in the field. *Journal of Economic Entomology* 92:435-438.
- Girard M, Chagnon M, Fournier V (2012) Pollen diversity collected by honey bees in the vicinity of *Vaccinium* spp. crops and its importance for colony development. *Botany-Botanique* 90:545-555. doi:10.1139/b2012-049
- Girardeau JH, Morgan LW, Leuck DB (1975) Honey bees and peanut hybridization. *Journal of the Georgia Entomological Society* 10:305-307.
- Giovenazzo P, Dubreuil P (2011) Evaluation of spring organic treatments against *Varroa destructor* (Acari: Varroidae) in honey bee *Apis mellifera* (Hymenoptera: Apidae) colonies in eastern Canada. *Experimental and Applied Acarology* 55:65-76. doi:10.1007/s10493-011-9447-3
- Gisder S, Hedtke K, Mockel N, Frielitz MC, Linde A, Genersch E (2010) Five-year cohort study of *Nosema* spp. in Germany: does climate shape virulence and assertiveness of *Nosema ceranae*? *Applied and Environmental Microbiology* 76:3032-3038. doi:10.1128/aem.03097-09
- Gisder S, Genersch E (2013) Molecular differentiation of *Nosema apis* and *Nosema ceranae* based on species-specific sequence differences in a protein coding gene. *Journal of Invertebrate Pathology* 113:1-6. doi:10.1016/j.jip.2013.01.004
- Godfray HCJ, Blacquière T, Field LM, Hails RS, Petrokofsky G, Potts SG, Raine NE, McLean AR (2014) A restatement of the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proceedings of the Royal Society B: Biological Sciences* 281:20140558. doi:10.1098/rspb.2014.0558 20140558

Godfray HCJ, Blacquière T, Field LM, Hails RS, Potts SG, Raine NE, McLean AR (2015) A restatement of recent advances in the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proceedings of the Royal Society B: Biological Sciences* 282:20151821. doi:10.1098/rspb.2015.1821

Goerzen DW, Erlandson MA, Bissett J (1990) Occurrence of chalkbrood caused by *Ascosphaera aggregata* Skou in a native leafcutting bee, *Megachile relative* Cresson (Hymenoptera: Megachilidae), in Saskatchewan. *The Canadian Entomologist* 122:1269-1270.

Goerzen DW, Dumouchel L, Bissett J (1992) Occurrence of chalkbrood caused by *Ascosphaera aggregata* Skou in a native leaf-cutting bee, *Megachile pugnata* Say (Hymenoptera, Megachilidae), in Saskatchewan. *The Canadian Entomologist* 124:557-558.

Goerzen DW, Richards KW, Rank GH (1995) Drifting in populations of the alfalfa leafcutting bee, *Megachile rotundata* (Fab) (Hym, Megachilidae). *Journal of Applied Entomology* 119:575-579.

Goettel MS, Richards KW (1991) Biology and control of chalkbrood, a fungal disease of the alfalfa leafcutter bee, *Megachile rotundata*. *Acta Horticulturae* (Wageningen) 288:386-390.

Goka K, Okabe K, Niwa S, Yoneda M (2000) Parasitic mite infestation in introduced colonies of European bumblebees, *Bombus terrestris*. *Japanese Journal of Applied Entomology and Zoology* 44:47-50.

Gonthier DJ, Ennis KK, Farinas S, Hsieh H-Y, Iverson AL, Batáry P, Rudolphi J, Tscharntke T, Cardinale BJ, Perfecto I (2014) Biodiversity conservation in agriculture requires a multi-scale approach. *Proceedings of the Royal Society B: Biological Sciences* 281:20141358. doi:10.1098/rspb.2014.1358 20141358

González-Varo JP, Arroyo J, Aparicio A (2009) Effects of fragmentation on pollinator assemblage, pollen limitation and seed production of Mediterranean myrtle (*Myrtus communis*). *Biological Conservation* 142:1058-1065. doi:10.1016/j.biocon.2009.01.017

González-Varo JP, Biesmeijer JC, Bommarco R, Potts SG, Schweiger O, Smith HG, Steffan-Dewenter I, Szentgyörgyi H, Woyciechowski M, Vila M (2013) Combined effects of global change pressures on animal-mediated pollination. *Trends in Ecology and Evolution* 28:524-530. doi:10.1016/j.tree.2013.05.008

Gordo O, Sanz JJ (2005) Phenology and climate change: a long-term study in a Mediterranean locality. *Oecologia* 146:484-495. doi:10.1007/s00442-005-0240-z

Gordo O, Sanz JJ, Lobo JM (2010) Determining the environmental factors underlying the spatial variability of insect appearance phenology for the honey bee, *Apis mellifera*, and the small white, *Pieris rapae*. *Journal of Insect Science* 10:34. doi:10.1673/031.010.3401.

Goulson D (2003a) Conserving wild bees for crop pollination. *Journal of Food Agriculture & Environment* 1:142-144.

Goulson D (2003b) Effects of introduced bees on native ecosystems. *Annual Review of Ecology Evolution and Systematics* 34:1-26. doi:10.1146/annurev.ecolsys.34.011802.132355

Goulson D (2013). An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology* 50:977-987. doi:10.1111/1365-2664.12111

- Goulson D (2015) Neonicotinoids impact bumblebee colony fitness in the field; a reanalysis of the UK's food & environment research agency 2012 experiment. *PeerJ* 3:e854. doi:10.7717/peerj.854
- Goulson D, Lepais O, O'Connor S, Osborne JL, Sanderson RA, Cussans J, Goffe L, Darvill B (2010) Effects of land use at a landscape scale on bumblebee nest density and survival. *Journal of Applied Ecology* 47:1207-1215. doi:10.1111/j.1365-2664.2010.01872.x
- Goulson D, Lye GC, Darvill B (2008) Decline and conservation of bumble bees. *Annual Review of Entomology* 53:191-208. doi:10.1146/annurev.ento.53.103106.093454
- Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:1255957. doi:10.1126/science.1255957
- Goulson D, Rayner O, Dawson B, Darvill B (2011) Translating research into action: bumblebee conservation as a case study. *Journal of Applied Ecology* 48:3-8. doi:10.1111/j.1365-2664.2010.01929.x
- Government of Ontario (2009) Pesticides act. R.S.O. 1990, Chapter p.11. <http://www.ontario.ca/laws/statute/90p11>
- Grabensteiner E, Nowotny N (2001) Virus infections of the honeybee (*Apis mellifera*). *Wiener Tierärztliche Monatsschrift* 88:79-87.
- Gradish AE, Scott-Dupree CD, Shipp L, Harris CR, Ferguson G (2010) Effect of reduced risk pesticides for use in greenhouse vegetable production on *Bombus impatiens* (Hymenoptera: Apidae). *Pest Management Science* 66:142-146. doi:10.1002/ps.1846
- Gradish AE, Scott-Dupree CD, Frewin AJ, Cutler GC (2012) Lethal and sublethal effects of some insecticides recommended for wild blueberry on the pollinator *Bombus impatiens*. *The Canadian Entomologist* 144:478-486. doi:10.4039/tce.2012.40
- Graham J, Tan Q, Jones L, Ellis J (2014) Native buzz: citizen scientists creating nesting habitat for solitary bees and wasps. *Florida Scientist* 77:204-218.
- Grange JM, Davey RW (1990) Antibacterial properties of propolis (bee glue). *Journal of the Royal Society of Medicine* 83:159-160.
- Graystock P, Yates K, Evison SEF, Darvill B, Goulson D, Hughes WOH (2013) The Trojan hives: pollinator pathogens, imported and distributed in bumblebee colonies. *Journal of Applied Ecology* 50:1207-1215. doi:10.1111/1365-2664.12134
- Graystock P, Goulson D, Hughes WOH (2014) The relationship between managed bees and the prevalence of parasites in bumblebees. *PeerJ* 2:e522. doi:10.7717/peerj.522 e522
- Greenaway W, Scasbroock T, Whatley FR (1990) The composition and plant origins of propolis: a report of work at Oxford. *Bee World* 71:107-108.
- Greenleaf SS, Kremen C (2006a) Wild bees enhance honey bees' pollination of hybrid sunflower. *Proceedings of the National Academy of Sciences of the United States of America* 103:13890-13895. doi:10.1073/pnas.0600929103
- Greenleaf SS, Kremen C (2006b). Wild bee species increase tomato production and respond differently to surrounding land use in Northern California. *Biological Conservation* 133:81-87. doi:10.1016/j.biocon.2006.05.025

- Greenleaf SS, Winfree R (2007) Bee foraging ranges and their relationship to body size. *Oecologia* 153:589–596.
- Grigorenko VN (1979) Distribution of *Apis mellifera* from wild honey flora to pollinating buckwheat crops. *Doklady MOIP Zoologiya i Botanika* 1977:64–66.
- Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. *Science* 319:756–760. doi:10.1126/science.1150195
- Grixti JC, Packer L (2006) Changes in the bee fauna (Hymenoptera: Apoidea) of an old field site in southern Ontario, revisited after 34 years. *The Canadian Entomologist* 138:147–164. doi:10.4039/n05-034
- Grixti JC, Wong LT, Cameron SA, Favret C (2009) Decline of bumble bees (*Bombus*) in the North American midwest. *Biological Conservation* 142:75–84. doi:10.1016/j.biocon.2008.09.027
- Gross CL (2001) The effect of introduced honeybees on native bee visitation and fruit-set in *Dillwynia juniperina* (Fabaceae) in a fragmented ecosystem. *Biological Conservation* 102:89–95. doi:10.1016/S0006-3207(01)00088-X
- Grzeda U, Gajda A, Topolska G (2014) Chronic bee paralysis and sacbrood: virus infections not associated with other bee diseases. *Medycyna Weterynaryjna-Veterinary Medicine-Science and Practice* 70:729–734.
- Gunnarsson B, Federsel LM (2014) Bumblebees in the city: abundance, species richness and diversity in two urban habitats. *Journal of Insect Conservation* 18:1185–1191. doi:10.1007/s10841-014-9729-2
- Guzman-Novoa E, Eccles L, Calvete Y, McGowan J, Kelly PG, Correa-Benitez A (2010) *Varroa destructor* is the main culprit for the death and reduced populations of overwintered honey bee (*Apis mellifera*) colonies in Ontario, Canada. *Apidologie* 41:443–450. doi:10.1051/apido/2009076
- Guzman-Novoa E, Emsen B, Unger P, Espinosa-Montano LG, Petukhova T (2012) Genotypic variability and relationships between mite infestation levels, mite damage, grooming intensity, and removal of *Varroa destructor* mites in selected strains of worker honey bees (*Apis mellifera* L.). *Journal of Invertebrate Pathology* 110:314–320. doi:10.1016/j.jip.2012.03.020
- Haaland C, Naisbit R, Bersier L (2011) Sown wildflower strips for insect conservation: a review. *Insect Conservation and Diversity* 4:60–80. doi:10.1111/j.1752-4598.2010.00098.x
- Hadley A, Betts M (2012) The effects of landscape fragmentation on pollination dynamics: absence of evidence not evidence of absence. *Biological Reviews* 87:526–544. doi:10.1111/j.1469-185X.2011.00205.x
- Hamiduzzaman MM, Guzman-Novoa E, Goodwin PH (2010) A multiplex PCR assay to diagnose and quantify *Nosema* infections in honey bees (*Apis mellifera*). *Journal of Invertebrate Pathology* 105:151–155. doi:10.1016/J.Jip.2010.06.001
- Hall IV, Aalders LE, Nickerson NL, Vanderkloet SP (1979) Biological flora of Canada *Vaccinium angustifolium* sweet lowbush blueberry. *Canadian Field-Naturalist* 93:415–430.

- Hall HG, Ascher JS (2011) Surveys of wild bees (Hymenoptera: Apoidea: *Anthophila*) in organic farms of Alachua county in north-central Florida. *Florida Entomologist* 94:539-552. doi:10.1653/024.094.0319
- Hallett P (2001) A method for 'having' solitary bees and wasps. *American Bee Journal* 141:133-136.
- Hanley ME, Wilkins JP (2015) On the verge? Preferential use of road-facing hedgerow margins by bumblebees in agro-ecosystems. *Journal of Insect Conservation* 19:67-74. doi:10.1007/s10841-014-9744-3
- Hannon LE, Sisk TD (2009) Hedgerows in an agri-natural landscape: potential habitat value for native bees. *Biological Conservation* 142:2140-2154. doi:10.1016/j.biocon.2009.04.014
- Hansted L, Grout BW, Toldam-Andersen TB, Eilenberg J (2015) Effectiveness of managed populations of wild and honey bees as supplemental pollinators of sour cherry (*Prunus cerasus* L.) under different climatic conditions. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science* 65:109-117. doi:10.1080/09064710.2014.971051
- Hanula J, Horn S (2011) Removing an invasive shrub (Chinese privet) increases native bee diversity and abundance in riparian forests of the southeastern United States. *Insect Conservation and Diversity* 4:275-283.
- Hanula JL, Ulyshen MD, Horn S (2016) Conserving pollinators in North American forests: a review. *Natural Areas Journal* 36:427-439. doi:10.3375/043.036.0409
- Harmon-Threatt AN, Hendrix SD (2015) Prairie restorations and bees: the potential ability of seed mixes to foster native bee communities. *Basic and Applied Ecology* 16:64- 72. doi:10.1016/j.baae.2014.11.0
- Harper-Lore B, Wilson M (2000) *Roadside Use of Native Plants*. Island Press, Washington D.C., USA.
- Harpur BA, Minaei S, Kent CF, Zayed A (2012) Management increases genetic diversity of honey bees via admixture. *Molecular Ecology* 21:4414-4421. doi:10.1111/J.1365-294x.2012.05614.X
- Harpur BA, Chernyshova A, Soltani A, Tsvetkov N, Mahjoorighasrodashti M, Xu Z, Zayed A (2014) No genetic tradeoffs between hygienic behaviour and individual innate immunity in the honey bee, *Apis mellifera*. *PLoS One* 9:e104214. doi:10.1371/journal.pone.0104214
- Harris CR, Svec HJ (1969) Laboratory studies on contact toxicity of some insecticides to honeybees. *Proceedings of the Entomological Society of Ontario* 100:165-167.
- Harrison JF, Camazine S, Marden JH, Kirkton SD, Roza A, Yang X (2001) Mite not make it home: tracheal mites reduce the safety margin for oxygen delivery of flying honeybees. *Journal of Experimental Biology* 204:805-814.
- Harrison T, Winfree R (2015) Urban drivers of plant-pollinator interactions. *Functional Ecology* 29:879-888. doi:10.1111/1365-2435.12486
- Hassan RR, Khater AM (2006) Influence of pollen substitutes on longevity and hypopharyngeal glands of caged honey bee workers (*Apis mellifera* L.). *Journal of Agricultural Science at Mansoura University* 31:419-427.

- Hausammann A (1996) Strip-management in rape crop: is winter rape endangered by negative impacts of sown weed strips? *Journal of Applied Entomology* 120:505-512.
- Havens K, Vitt P (2016) The Importance of Phenological Diversity in Seed Mixes for Pollinator Restoration. *Natural Areas Journal*. 36:531-537. doi:10.3375/043.036.0419
- Heard MS, Carvell C, Carreck NL, Rothery P, Osborne JL, Bourke AFG (2008) Landscape context not patch size determines bumble-bee density on flower mixtures sown for agri-environment schemes. *Biology Letters* 3:638-641. doi:10.1098/rsbl.2007.0425
- Hegland SJ, Nielsen A, Lazaro A, Bjerknes AL, Totland O (2009) How does climate warming affect plant-pollinator interactions? *Ecology Letters* 12:184-195. doi:10.1111/j.1461-0248.2008.01269.x
- Helson BV, Barber KN, Kingsbury PD (1994) Laboratory toxicology of 6 forestry insecticides to 4 species of bee (Hymenoptera, Apoidea). *Archives of Environmental Contamination and Toxicology* 27:107-114.
- Hendrickx F, Maelfait JP, Van Wingerden W, Schweiger O, Speelmans M, Aviron S, Augenstein I, Billeter R, Bailey D, Bukacek R, et al. (2007) How landscape structure, land-use intensity and habitat diversity affect components of total arthropod diversity in agricultural landscapes. *Journal of Applied Ecology* 44:340-351. doi:10.1111/j.1365-2664.2006.01270.x
- Henne CS, Rodriguez E, Adamczyk JJ Jr (2012) A survey of bee species found pollinating watermelons in the lower Rio Grande Valley of Texas. *Psyche* 2012:1-5. doi:10.1155/2012/357250
- Hennig EI, Ghazoul J (2012) Pollinating animals in the urban environment. *Urban Ecosystems* 15:149-166. doi:10.1007/s11252-011-0202-7
- Henry M, Béguin M, Requier F, Rollin O, Odoux JF, Aupinel P, Decourtye A (2012a) A common pesticide decreases foraging success and survival in honey bees. *Science* 336:348-350. doi:10.1126/science.1215039
- Henry M, Béguin M, Requier F, Rollin O, Odoux JF, Aupinel P, Aptel J, Tchamitchian S, Decourtye A (2012b) Response to comment on "A common pesticide decreases foraging success and survival in honey bees". *Science* 337:1453. doi:10.1126/science.1224930
- Herbert LT, Vazquez DE, Arenas A, Farina WM (2014) Effects of field-realistic doses of glyphosate on honeybee appetitive behaviour. *Journal of Experimental Biology* 217:3457-3464. doi:10.1242/jeb.109520
- Herron CM, Jonas JL, Meiman PJ, Paschke MW (2013) Using native annual plants to restore post-fire habitats in western North America. *International Journal of Wildland Fire* 22:815-821. doi:10.1071/wf11179
- Heywood VH (1995) *Global Biodiversity Assessment*. Cambridge University Press, Cambridge, Massachusetts, USA.
- Hicks DM, Ouvrard P, Baldock KCR, Baude M, Goddard MA, Kunin WE, Mitschunas N, Memmott J, Morse H, Nikolitsi M et al. (2016). Food for pollinators: quantifying the nectar and pollen resources of urban flower meadows. *PLoS One* 11:e0158117. doi:10.1371/journal.pone.0158117

- Highfield AC, El Nagar A, Mackinder LCM, Noel LMLJ, Hall MJ, Martin SJ, Schroeder DC (2009) Deformed wing virus implicated in overwintering honeybee colony losses. *Applied and Environmental Microbiology* 75:7212-7220. doi:10.1128/aem.02227-09
- Higo HA, Rice ND, Winston ML, Lewis B (2004) Honey bee (Hymenoptera: Apidae) distribution and potential for supplementary pollination in commercial tomato greenhouses during winter. *Journal of Economic Entomology* 97:163-170. doi:10.1603/0022-0493-97.2.163
- Hillier NK, Frost EH, Shutler D (2013) Fate of dermally applied miticides fluvalinate and amitraz within honey bee (Hymenoptera: Apidae) bodies. *Journal of Economic Entomology* 106:558-565. doi:10.1603/ec12300
- Hinners SJ, Kearns CA, Wessman CA (2012) Roles of scale, matrix, and native habitat in supporting a diverse suburban pollinator assemblage. *Ecological Applications* 22:1923-1935. doi:10.1890/11-1590.1
- Hladun KR, Di N, Liu TX, Trumble JT (2016). Metal contaminant accumulation in the hive: consequences for whole-colony health and brood production in the honey bee (*Apis mellifera* L.). *Environmental Toxicology and Chemistry* 35:322-329. doi:10.1002/etc.3273
- Hladun KR, Kaftanoglu O, Parker DR, Tran KD, Trumble JT (2013). Effects of selenium on development, survival, and accumulation in the honeybee (*Apis mellifera* L.). *Environmental Toxicology and Chemistry* 21:2584-2592. doi:10.1002/etc.2357
- Hladun KR, Smith BH, Mustard JA, Morton RR, Trumble JT (2012). Selenium toxicity to honey bee (*Apis mellifera* L.) pollinators: effects on behaviors and survival. *PLoS One* 7:e34137. doi:10.1371/journal.pone.0034137
- Hobbs GA (1956) Ecology of the leaf-cutter bee *Megachile perhirta* Ckll. (Hymenoptera: Megachilidae) in relation to production of alfalfa seed. *The Canadian Entomologist* 87:625-629.
- Hoffmann F, Kwak MM (2007) Diversity of flowering plants and flower visiting insects in relation to land use. *Entomologische Berichten* 67:193-197.
- Hoffmann D, Pettis JS, Neumann P (2008) Potential host shift of the small hive beetle (*Aethina tumida*) to bumblebee colonies (*Bombus impatiens*). *Insectes Sociaux* 55:153-162. doi:10.1007/s00040-008-0982-9
- Hole DG, Perkins AJ, Wilson JD, Alexander IH, Grice PV, Evans AD (2005) Does organic farming benefit biodiversity? *Biological Conservation* 122:113-130. doi:10.1016/j.biocon.2004.07.018
- Holland JM, Smith BM, Storkey J, Lutman PJW, Aebischer NJ (2015) Managing habitats on English farmland for insect pollinator conservation. *Biological Conservation* 182:215-222. doi:10.1016/j.biocon.2014.12.009
- Holloway PS, Kruse JJ, Davis AN (2003) Insect visitors and potential pollinators of lingonberries, *Vaccinium vitis-idaea* subsp *minus*, in sub-arctic Alaska. Twenty-sixth International Horticultural Congress: Berry Crop Breeding, Production and Utilization for a New Century 626:433-438. doi:10.17660/ActaHortic.2003.626.60
- Holzschuh A, Steffan-Dewenter I, Tscharntke T (2008) Agricultural landscapes with organic crops support higher pollinator diversity. *Oikos* 117:354-361. doi:10.1111/j.2007.0030-1299.16303.x

- Holzschuh A, Steffan-Dewenter I, Tschardt T (2010) How do landscape composition and configuration, organic farming and fallow strips affect the diversity of bees, wasps and their parasitoids? *Journal of Animal Ecology* 79:491-500. doi:10.1111/j.1365-2656.2009.01642.x
- Holzschuh A, Dudenhöffer JH, Tschardt T (2012) Landscapes with wild bee habitats enhance pollination, fruit set and yield of sweet cherry. *Biological Conservation* 153:101-107. doi:10.1016/j.biocon.2012.04.032
- Holzschuh A, Dormann CF, Tschardt T, Steffan-Dewenter I (2013) Mass-flowering crops enhance wild bee abundance. *Oecologia* 172:477-484. doi:10.1007/s00442-012-2515-5
- Holzschuh A, Dainese M, González-Varo JP, Mudri-Stojnic S, Riedinger V, Rundlöf M, Scheper J, Wickens JB, Wickens VJ, Bommarco R, et al. (2016). Mass-flowering crops dilute pollinator abundance in agricultural landscapes across Europe. *Ecology Letters* 1228-1236. doi:10.1111/ele.12657
- Hoover SER, Ladley JJ, Shchepetkina AA, Tisch M, Giese SP, Tylianakis JM (2012) Warming, CO<sub>2</sub>, and nitrogen deposition interactively affect a plant-pollinator mutualism. *Ecology Letters* 15:227-234. doi:10.1111/j.1461-0248.2011.01729.x
- Hoover SER, Hoover T (2014) Impact of environmental change on honey bees and beekeeping. pp. 463-479 in *Beekeeping for Poverty Alleviation and Livelihood Security: Technological Aspects of Beekeeping*. Eds. Gupta RK, Reybroeck W, van Veen JW, Gupta A. Springer, New York, New York, USA.
- Hopfenmüller S, Steffan-Dewenter I, Holzschuh A (2014) Trait-specific responses of wild bee communities to landscape composition, configuration and local factors. *PLoS One* 9:e104439. doi:10.1371/journal.pone.0104439
- Hopwood JL (2008) The contribution of roadside grassland restorations to native bee conservation. *Biological Conservation* 141:2632-2640. doi:10.1016/j.biocon.2008.07.026
- Horn M (2010) A comparison of pollinator biodiversity between green spaces, industrial areas and residential land-use zones in urban, southern Ontario. MSc thesis, University of Guelph, Guelph, Ontario, Canada.  
<http://www.uoguelph.ca/canpolin/Publications/Horn%20MSc%202010.pdf>
- Horskins K, Turner B (1999) Resource use and foraging patterns of honeybees, *Apis mellifera*, and native insects on flowers of *Eucalyptus costata*. *Australian Journal of Ecology* 24:221-227.
- Huang Z (2012) Pollen nutrition affects honey bee stress resistance. *Terrestrial Arthropod Reviews* 5:175-189. doi:10.1163/187498312x639568
- Huey RB, Deutsch CA, Tewksbury JJ, Vitt LJ, Hertz PE, Alvarez Perez HJ, Garland T Jr (2009) Why tropical forest lizards are vulnerable to climate warming. *Proceedings of the Royal Society B: Biological Sciences* 276:1939-1948. doi:10.1098/rspb.2008.1957
- Hurd PD Jr, Linsley EG, Whitaker TW (1971) Squash and gourd bees (*Peponapis*, *Xenoglossa*) and the origin of the cultivated Cucurbita. *Evolution* 25:218-234.
- Hunt G, Krupke C (2012) Managed pollinator CAP coordinated agricultural project a national research and extension initiative to reverse pollinator decline neonicotinoid seed treatments and honey bee health. *American Bee Journal* 152:889-891.



Hunter W, Ellis J, vanEngelsdorp D, Hayes J, Westervelt D, Glick E, Williams M, Sela I, Maori E, Pettis J, et al. (2010) Large-scale field application of RNAi technology reducing Israeli acute paralysis virus disease in honey bees (*Apis mellifera*, Hymenoptera: Apidae). PLoS Pathogens 6:e1001160. doi:10.1371/journal.ppat.1001160

Hydro One Inc. (2006) *Transmission System Map*. Toronto, Ontario, Canada.

[http://www.hydroone.com/RegulatoryAffairs/Documents/EB-2006-0501/Exhibit%20A/Tab\\_6\\_Sched\\_1-Transmission\\_System\\_Map.pdf](http://www.hydroone.com/RegulatoryAffairs/Documents/EB-2006-0501/Exhibit%20A/Tab_6_Sched_1-Transmission_System_Map.pdf)

Hydro One Inc. (2009) *Vegetation Management*. Toronto, Ontario, Canada.

<http://www.hydroone.com/OurCommitment/Environment/Pages/Vegetation.aspx>

Ibarra-Perez FJ, Barnhart D, Ehdaie B, Knio KM, Waines JG (1999) Effects of insect tripping on seed yield of common bean. Crop Science 39:428-433.

Imhoof B, Schmid-Hempel P (1999) Colony success of the bumble bee, *Bombus terrestris*, in relation to infections by two protozoan parasites, *Crithidia bombi* and *Nosema bombi*. Insectes Sociaux 46:233-238.

Ings TC, Raine NE, Chittka L (2005) Mating preference of commercially imported bees (*Bombus terrestris*) in Britain (Hymenoptera: Apidae). Entomologia Generalis 28:233-238. doi:10.1127/entom.gen/28/2005/233

IPBES (2016). The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. S.G. Potts, V. L. Imperatriz-Fonseca, and H. T. Ngo, (eds). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 552 pages.

Isaacs R, Tuell J, Fiedler A, Gardiner M, Landis D (2009) Maximizing arthropod-mediated ecosystem services in agricultural landscapes: the role of native plants. Frontiers in Ecology and the Environment 7:196-203. doi:10.1890/080035

Isaacs R, Kirk AK (2010) Pollination services provided to small and large highbush blueberry fields by wild and managed bees. Journal of Applied Ecology 47:841-849. doi:10.1111/j.1365-2664.2010.01823.x

Iselin WA, Jensen MH, Spangler HG (1974) Pollination of melons in air inflated greenhouses by honey bees. Environmental Entomology 3:664-666.

Jack CJ, Lucas HM, Webster TC, Sagili RR (2016) Colony level prevalence and intensity of *Nosema ceranae* in honey bees (*Apis mellifera* L.). PLoS One 11:e0163522. doi:10.1371/journal.pone.0163522

Jahns TR, Jolliff GD (1991) Survival rate and reproductive success of *Osmia lignaria propinqua* Cresson (Hymenoptera: Megachilidae) in caged meadowfoam, *Limnanthes alba* benth (Limnanthaceae). Journal of the Kansas Entomological Society 64:95-106.

James RJ, Pitts-Singer TL (2008) *Bee Pollination in Agricultural Ecosystems*. Oxford University Press, New York, New York, USA.

James RR (2011) Chalkbrood transmission in the alfalfa leafcutting bee: the impact of disinfecting bee cocoons in loose cell management systems. Environmental Entomology 40:782-787.

- James DG, Seymour L, Lauby G, Buckley K (2014) Beneficial insects attracted to native flowering buckwheats (*Eriogonum michx*) in central Washington. *Environmental Entomology* 43:942-948. doi:10.1603/en13342
- Janmaat AF, Winston ML (2000) Removal of *Varroa jacobsoni* infested brood in honey bee colonies with different pollen stores. *Apidologie* 31:377-385.
- Jensen AB, Palmer KA, Boomsma JJ, Pedersen BV (2005) Varying degrees of *Apis mellifera ligustica* introgression in protected populations of the black honeybee, *Apis mellifera mellifera*, in northwest Europe. *Molecular Ecology* 14:93-106. doi:10.1111/j.1365-294X.2004.02399.x
- Jha S, Kremen C (2013) Resource diversity and landscape-level homogeneity drive native bee foraging. *Proceedings of the National Academy of Sciences of the United States of America* 110:555-558. doi:10.1073/pnas.1208682110
- Jha S, Stefanovich L, Kremen C (2013) Bumble bee pollen use and preference across spatial scales in human-altered landscapes. *Ecological Entomology* 38:570-579. doi:10.1111/een.12056
- Jue DK, Daniels JC (2015) A successful model for citizen scientist involvement in building a statewide at-risk butterfly database. *Journal of Insect Conservation* 19:421-431. doi:10.1007/s10841-014-9733-6
- Johansen CA, Mayer DF, Eves JD, Kious CW (1983) Pesticides and bees. *Environmental Entomology* 12:1513-1518.
- Johnson BR, Synk W, Jasper WC, Mussen E (2014) Effects of high fructose corn syrup and probiotics on growth rates of newly founded honey bee colonies. *Journal of Apicultural Research* 53:165-170. doi:10.3896/ibra.1.53.1.18
- Johnson R (2010) *Honey Bee Colony Collapse Disorder*. Congressional Research Service, Washington D.C., USA. <https://fas.org/sgp/crs/misc/RL33938.pdf>.
- Johnson RM, Pollock HS, Berenbaum MR (2009) Synergistic interactions between in-hive miticides in *Apis mellifera*. *Journal of Economic Entomology* 102:474-479. doi:10.1603/029.102.0202
- Johnson RM, Ellis MD, Mullin CA, Frazier M (2010) Pesticides and honey bee toxicity - USA. *Apidologie* 41:312-331. doi:10.1051/apido/2010018
- Johnson RM, Dahlgren L, Siegfried BD, Ellis MD (2013) Acaricide, fungicide and drug interactions in honey bees (*Apis mellifera*). *PLoS One* 8:e54092. doi:10.1371/journal.pone.0054092
- Julier HE, Roulston TH (2007). Without honeybees, wild bees may still provide full pollination service on cultivated pumpkins. *Ecological Society of America Annual Meeting Abstracts*. San Jose McEnery Convention Center Aug 5-Aug 10, 2007. San Jose, California, USA. <http://esameetings.allenpress.com/2007/P8769.HTM>
- Julier HE, Roulston TH (2009) Wild bee abundance and pollination service in cultivated pumpkins: farm management, nesting behavior and landscape effects. *Journal of Economic Entomology* 102:563-573. doi:10.1603/029.102.0214
- Kanbe Y, Okada I, Yoneda M, Goka K, Tsuchida K (2008) Interspecific mating of the introduced bumblebee *Bombus terrestris* and the native Japanese bumble *Bombus*

*hypocrita sapporoensis* results in inviable hybrids. *Naturwissenschaften* 95:1003-1008. doi:10.1007/s00114-008-0415-7

Karron JD (1987) The pollination ecology of co-occurring geographically restricted and widespread species of *Astragalus* (Fabaceae). *Biological Conservation* 39:179-193. doi:10.1016/0006-3207(87)90033-4

Kauffeld NM, Williams PH (1972) Honey bees as pollinators of picking cucumbers-d in Wisconsin. *American Bee Journal* 112:252-254.

Kauffeld NM, Hernandez T, Wright J, Misaraca S (1975) Cucumber production in Louisiana USA with honey bees as pollinators. *American Bee Journal* 115:252-254.

Kavitha P, Rao JV (2008) Toxic effects of chlorpyrifos on antioxidant enzymes and target enzyme acetylcholinesterase interaction in mosquito fish, *Gambusia affinis*. *Environmental Toxicology and Pharmacology* 26:192-198. doi:10.1016/J.Etap.2008.03.010

Kearns CA, Inouye DW, Waser NM (1998) Endangered mutualisms: the conservation of plant-pollinator interactions. *Annual Review of Ecology and Systematics* 29:83-112.

Kearns CA (2001) North American, dipteran pollinators: assessing their value and conservation status. *Conservation Ecology* 5:5.

Kearns CA, Oliveras DM (2009) Environmental factors affecting bee diversity in urban and remote grassland plots in Boulder, Colorado. *Journal of Insect Conservation* 13:655-665. doi:10.1007/s10841-009-9215-4

Kells AR, Holland JM, Goulson D (2001) The value of uncropped field margins for foraging bumblebees. *Journal of Insect Conservation* 5:283-291. doi:10.1023/A:1013307822575

Kemp WP, Bosch J (2000) Development and emergence of the alfalfa pollinator *Megachile rotundata* (Hymenoptera: Megachilidae). *Annals of the Entomological Society of America* 93:904-911. doi:10.1603/00138746(2000)093[0904:daeota]2.0.co;2

Kemp WP, Bosch J (2005) Effect of temperature on *Osmia lignaria* (Hymenoptera: Megachilidae) prepupa-adult development, survival, and emergence. *Journal of Economic Entomology* 98:1917-1923. doi:10.1093/jee/98.6.1917 1

Kendall DA (1973) Viability and compatibility of pollen on insects visiting apple blossom *Journal of Applied Ecology* 10:847-853. doi:10.2307/2401873

Kendall DA, Solomon ME (1973) Quantities of pollen on bodies of insects visiting apple blossom. *Journal of Applied Ecology* 10:627-634. doi:10.2307/2402306

Kendall DA, Smith BD (1976) Pollinating efficiency of honeybee and bumblebee visits to flowers of runner bean *Phaseolus coccineus* L. *Journal of Applied Ecology* 13:749-752. doi:10.2307/2402252

Kerr JT (2001) Butterfly species richness patterns in Canada: energy, heterogeneity, and the potential consequences of climate change. *Ecology and Society* 5:1-14.

Kerr JT, Pindar A, Galpern P, Packer L, Potts SG, Roberts SPM, Rasmont P, Schweiger O, Colla SR, Richardson L, et al. (2015). Climate change impacts on bumblebees converge across continents. *Science* 349:177-180. doi:10.1126/science.aaa7031

Kerr JT, Vincent R, Currie DJ (1998) Lepidopteran richness patterns in North America. *Ecoscience* 5:448-453.

- Kessler SC, Tiedeken EJ, Simcock KL, Derveau S, Mitchell J, Softley S, Stout JC, Wright GA (2015) Bees prefer foods containing neonicotinoid pesticides. *Nature* 521:74-76. doi:10.1038/nature14414
- Kevan PG, Clark EA, Thomas VG (1990) Insect pollinators and sustainable agriculture. *American Journal of Alternative Agriculture* 5:13-22.
- Kevan PG (1991) Honey bees (*Apis mellifera*, Hymenoptera, Apidae) and fonos on sweet corn (*Zea mays*, Poaceae). *Proceedings of the Entomological Society of Ontario* 122:35-40.
- Kevan PG, Straver WA, Offer M, Lavery TM (1991) Pollination of greenhouse tomatoes by bumble bees in Ontario. *Proceedings of the Entomological Society of Ontario* 122:15-19.
- Kevan PG, Phillips TP (2001) The economic impacts of pollinator declines: an approach to assessing the consequences. *Conservation Ecology* 5:8.
- Kevan PG, Viana BF (2003) The global decline of pollination services. *Biodiversity* 4:3-8.
- Kevan PG, Hannan MA, Ostiguy N, Guzman-Novoa E (2006) A summary of the *Varroa*-virus disease complex in honey bees. *American Bee Journal* 146:694-697.
- Kevan PG, Guzman E, Skinner A, vanEnglesdorp D (2007) Colony collapse disorder (CCD) in Canada: do we have a problem? *Hivelights* 20:15-18.
- Kharouba HM, Algar AC, Kerr JT (2009) Historically calibrated predictions of butterfly species' range shift using global change as a pseudo-experiment. *Ecology* 90:2213-2222. doi:10.1890/08-1304.1
- Kim J, Williams N, Kremen C (2006) Effects of cultivation and proximity to natural habitat on ground-nesting native bees in California sunflower fields. *Journal of the Kansas Entomological Society* 79:309-320. doi:10.2317/0507.11.1
- Klatt BK, Holzschuh A, Westphal C, Clough Y, Smit I, Pawelzik E, Tschardt T (2014) Bee pollination improves crop quality, shelf life and commercial value. *Proceedings of the Royal Society B: Biological Sciences* 281:20132440. doi:10.1098/rspb.2013.2440
- Kleijn D, Snoeijing G (1997) Field boundary vegetation and the effects of agrochemical drift: botanical change caused by low levels of herbicide and fertilizer. *Journal of Applied Ecology* 34:1413-1425.
- Kleijn D, Berendse F, Smit R, Gilissen N (2001) Agri-environment schemes do not effectively protect biodiversity in Dutch agricultural landscapes. *Nature* 413:723-725.
- Kleijn D, Sutherland W (2003) How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology* 40:947-969. doi:10.1111/j.1365-2664.2003.00868.x
- Kleijn D, Baquero RA, Clough Y, Diaz M, De Esteban J, Fernandez F, Gabriel D, Herzog F, Holzschuh A, Jöhl R, et al. (2006) Mixed biodiversity benefits of agri-environment schemes in five European countries. *Ecology Letters* 9:243-254. doi:10.1111/j.1461-0248.2005.00869.x
- Kleijn D, Winfree R, Bartomeus I, Carvalheiro LG, Henry M, Isaacs R, Klein A-M, Kremen C, Rader R, Ricketts TH, et al. (2015) Delivery of crop pollination services is an

insufficient argument for wild pollinator conservation. *Nature Communications* 6:7414. doi:10.1038/ncomms8414

Klein A-M, Steffan-Dewenter I, Tscharntke T (2003) Fruit set of highland coffee increases with the diversity of pollinating bees. *Proceedings of the Royal Society B: Biological Sciences* 270:955-961. doi:10.1098/rspb.2002.2306

Klein A-M, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* 274:303-313. doi:10.1098/rspb.2006.3721

Klein A-M, Brittain C, Hendrix SD, Thorp R, Williams N, Kremen C (2012) Wild pollination services to California almond rely on semi-natural habitat. *Journal of Applied Ecology* 49:723-732. doi:10.1111/j.1365-2664.2012.02144.x

Knop E, Kleijn D, Herzog F, Schmid B (2006) Effectiveness of the Swiss agri-environment scheme in promoting biodiversity. *Journal of Applied Ecology* 43:120-127. doi:10.1111/j.1365-2664.2005.01113.x

Koelling PD, Kenworthy WJ, Caron DM (1981) Pollination of male-sterile soybeans in caged plots. *Crop Science* 21:559-561.

Koh I, Lonsdorf EV, Williams NM, Brittain C, Isaacs R, Gibbs J, Ricketts TH 2016 Modeling the status, trends, and impacts of wild bee abundance in the United States. *Proceedings of the National Academy of Sciences of the United States of America* 113:140-5. doi:10.1073/pnas.1517685113

Kohler F, Verhulst J, Knop E, Herzog F, Kleijn D (2007) Indirect effects of grassland extensification schemes on pollinators in two contrasting European countries. *Biological Conservation* 135:302-307. doi:10.1016/j.biocon.2006.10.037

Kovac H, Kafer H, Stabentheiner A, Costa C (2014) Metabolism and upper thermal limits of *Apis mellifera carnica* and *A. m. ligustica*. *Apidologie* 45:664-677. doi:10.1007/s13592-014-0284-3

Kovács-Hostyánszki A, Körösi A, Orci K, Batáry P, Báldi A (2011) Set-aside promotes insect and plant diversity in a central European country. *Agriculture, Ecosystems & Environment* 141:296-301. doi:10.1016/j.agee.2011.03.004

Kovács-Hostyánszki A, Haenke S, Batáry P, Jauker B, Báldi A, Tscharntke T, Holzschuh A (2013) Contrasting effects of mass-flowering crops on bee pollination of hedge plants at different spatial and temporal scales. *Ecological Applications* 23:1938-1946. doi:10.1890/12-2012.1

Kozak P (2010a) Small hive beetle found in southern Ontario. *Hivelights* 24:30.

Kozak P (2010b) 2010 Provincial Apiarist Annual Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada. <http://www.omafra.gov.on.ca/english/food/inspection/bees/10rep.htm>

Kozak P (2012a) 2011 Ontario Provincial Apiarist Annual Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada. <http://www.omafra.gov.on.ca/english/food/inspection/bees/11rep.htm>

Kozak P (2012b) Varroa mite–biology and diagnosis. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

<http://www.omafra.gov.on.ca/english/food/inspection/bees/varroa-biology.htm>

Kozak P (2012c) American foulbrood–biology and diagnosis. Ontario Ministry of Agriculture Food and Rural Affairs. Guelph, Ontario

<http://www.omafra.gov.on.ca/english/food/inspection/bees/afb-biology.htm>

Kozak P (2013) 2012 Provincial Apiarist Annual Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

<http://www.omafra.gov.on.ca/english/food/inspection/bees/12rep.htm>

Kozak P (2014) 2013 Provincial Apiarist Annual Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

<http://www.omafra.gov.on.ca/english/food/inspection/bees/13rep.htm>

Kozak P (2015a) 2014 Provincial Apiarist Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

<http://www.omafra.gov.on.ca/english/food/inspection/bees/14rep.htm>

Kozak P (2015b) Ontario honey bee colony winter loss survey report for 2014. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

Kozak P (2016) 2015 Provincial Apiarist Report. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

<http://www.omafra.gov.on.ca/english/food/inspection/bees/15rep.htm>

Kraemer ME, Favi FD (2005) Flower phenology and pollen choice of *Osmia lignaria* (Hymenoptera: Megachilidae) in central Virginia. *Environmental Entomology* 34:1593-1605. doi:10.1603/0046-225X-34.6.1593

Krauss J, Alfert T, Steffan-Dewenter I (2009) Habitat area but not habitat age determines wild bee richness in limestone quarries. *Journal of Applied Ecology* 46:194-202.

doi:10.1111/j.1365-2664.2008.01582.x

Krell R (1996) *Value Added Products from Beekeeping*. Food and Agriculture Organization of the United Nations, Rome, Italy, UK.

Kremen C, Williams NM, Thorp RW (2002a) Crop pollination from native bees at risk from agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America* 99:16812-1816. doi:10.1073/pnas.262413599

Kremen C, Bugg RL, Nicola N, Smith SA, Thorp RW, Williams NM (2002b) Native bees, native plants and crop pollination in California. *Fremontia* 30:41-49.

Kremen C, Williams NM, Bugg RL, Fay JP, Thorp RW (2004) The area requirements of an ecosystem service: crop pollination by native bee communities in California. *Ecology Letters* 7:1109-1119. doi:10.1111/j.1461-0248.2004.00662.x

Kremen C, Williams NM, Aizen MA, Gemmill-Herren B, LeBuhn G, Minckley R, Packer L, Potts SG, Roulston TH, Steffan-Dewenter I, et al. (2007) Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. *Ecology Letters* 10:299-314. doi:10.1111/j.1461-0248.2007.01018.x

Kremen C (2008) Crop pollination services from wild bees. pp. 10-26 in *Bee Pollination in Agricultural Ecosystems*. Eds. James RR, Pitts-Singer TL. Oxford University Press, New York, New York, USA.

Kremen C, M'Gonigle LK, Diamond S (2015) Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. *Journal of Applied Ecology* 52:602-610. doi:10.1111/1365-2664.12418

Kroyer G, Hegedus N (2001) Evaluation of bioactive properties of pollen extracts as functional dietary food supplement. *Innovative Food Science & Emerging Technologies* 2:171-174.

Krunic MD, Hinks CF (1972) The effect of temperature and of temperature pretreatment on diapause and on the synchronization of adult emergence in *Megachile rotundata* (Hymenoptera: Megachilidae). *The Canadian Entomologist* 104: 889-893.

Krupke CH, Hunt GJ, Eitzer BD, Andino G, Given K (2012) Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One* 7:e29268. doi:10.1371/journal.pone.0029268.

Kubišová S, Háslbachová H (1990) Pollination of male-sterile green pepper line (*Capsicum annuum* L.) by honeybees. *Sixth International Symposium on Pollination* 288:364-370.

Kuussaari M, Hyvönen T, Härmä O (2011) Pollinator insects benefit from rotational fallows. *Agriculture, Ecosystems & Environment* 143:28-36. doi:10.1016/j.agee.2011.03.006

LaBar T, Campbell C, Yang S, Albert R, Shea K (2014) Restoration of plant-pollinator interaction networks via species translocation. *Theoretical Ecology* 7:209-220. doi:10.1007/s12080-013-0211-7

Lacey B (2014) A two year study of *Nosema ceranae* in Ontario. *Ontario Bee Journal* 33:14-16.

Lach L (2008) Argentine ants displace floral arthropods in a biodiversity hotspot. *Diversity and Distributions* 14:281-290. doi:10.1111/j.1472-4642.2007.00410.x

Lait CG, Borden JH, Kovacs E, Moeri OE, Campbell M, Machial CM (2012) Treatment with synthetic brood pheromone (SuperBoost) enhances honey production and improves overwintering survival of package honey bee (Hymenoptera: Apidae) colonies. *Journal of Economic Entomology* 105:304-312. doi:10.1603/ec11285

Landis DA, Menalled FD, Costamagna AC, Wilkinson TK (2005) Manipulating plant resources to enhance beneficial arthropods in agricultural landscapes. *Weed Science* 53:902-908. doi:10.1614/WS-04-050R1.1

Langridge DF, Jenkins PT (1970) The role of honey bees in pollination of apple. *Australian Journal of Experimental Agriculture and Animal Husbandry* 10:366-36.

Larson JL, Redmond CT, Potter DA (2013) Assessing insecticide hazard to bumble bees foraging on flowering weeds in treated lawns. *PLoS One* 8:e66375. doi:10.1371/journal.pone.0066375

Larson JL, Kesheimer AJ, Potter DA (2014) Pollinator assemblages on dandelions and white clover in urban and suburban lawns. *Journal of Insect Conservation* 18:863-873. doi:10.1007/s10841-014-9694-9

- Lautenbach S, Seppelt R, Liebscher J, Dormann CF (2012) Spatial and temporal trends of global pollination benefit. *PLoS One* 7:e35954. doi:10.1371/journal.pone.0035954
- Lavergne S, Molina J, Debussche M (2006) Fingerprints of environmental change on the rare mediterranean flora: a 115-year study. *Global Change Biology* 12:1466-1478. doi:10.1111/j.1365-2486.2006.01183.x
- Lavergne S, Mouquet N, Thuiller W, Ronce O (2010) Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities. *Annual Review of Ecology, Evolution, and Systematics* 41:321-350. doi:10.1146/annurev-ecolsys-102209-144628
- Laycock I, Cresswell JE (2013) Repression and recuperation of brood production in *Bombus terrestris* bumble bees exposed to a pulse of the neonicotinoid pesticide imidacloprid. *PLoS One* 8:e79872. doi:10.1371/journal.pone.0079872
- Laycock I, Lenthall KM, Barratt AT, Cresswell JE (2012) Effects of imidacloprid, a neonicotinoid pesticide, on reproduction in worker bumble bees (*Bombus terrestris*). *Ecotoxicology* 21:1937-1945. doi:10.1007/s10646-012-0927-y
- Laycock I, Cotterell KC, O'Shea-Wheller TA, Cresswell JE (2014) Effects of the neonicotinoid pesticide thiamethoxam at field-realistic levels on microcolonies of *Bombus terrestris* worker bumble bees. *Ecotoxicology and Environmental Safety* 100:153-158. doi:10.1016/j.ecoenv.2013.10.027
- Le Conte Y, Navajas M (2008) Climate change: impact on honey bee populations and diseases. *Revue Scientifique et Technique - Office International Des Epizooties* 27:499-510.
- Le Conte Y, Ellis M, Ritter W (2010) *Varroa* mites and honey bee health: can *Varroa* explain part of the colony losses? *Apidologie* 41:353-363. doi:10.1051/apido/2010017
- Le Féon V, Schermann-Legionnet A, Delettre Y, Aviron S, Billeter R, Bugter R, Hendrickx F, Burel F (2010) Intensification of agriculture, landscape composition and wild bee communities: a large scale study in four European countries. *Agriculture, Ecosystems & Environment* 137:143-150. doi:10.1016/j.agee.2010.01.015
- Le Féon V, Burel F, Chifflet R, Henry M, Ricroch A, Vaissière BE, Baudry J (2013) Solitary bee abundance and species richness in dynamic agricultural landscapes. *Agriculture, Ecosystems & Environment* 166:94-101. doi:10.1016/j.agee.2011.06.020
- Leguen J, Mesquida J, Pierre JS, Morin G, Tasei JN, Carre S (1993) Efficiency of pollination treatments on 2 lines of spring faba bean (*Vicia faba* L Var Equina Steudel), with different levels of self-fertility and using 3 subspecies of *Bombus* Latr (Hymenoptera, Apidae). *Apidologie* 24:129-145. doi:10.1051/apido:19930206
- Lesley J, Lesley M (1939) Unfruitfulness in the tomato caused by male sterility. *Journal of Agricultural Resources* 58:621-630.
- Lewis W, van Lenteren J, Phatak S, Tumlinson J (1997) A total system approach to sustainable pest management. *Proceedings of the National Academy of Sciences of the United States of America* 94:12243-12248.
- Lindberg CM, Melathopoulos AP, Winston ML (2000) Laboratory evaluation of miticides to control *Varroa jacobsoni* (Acari: Varroidae), a honey bee (Hymenoptera: Apidae) parasite. *Journal of Economic Entomology* 93:189-198.



- Lindsay KE, Kirk DA, Bergin TM, Best LB, Sifneos JC, Smith J (2013) Farmland heterogeneity benefits birds in American mid-west watersheds. *American Midland Naturalist* 170:121-143. doi:10.1674/0003-0031-170.1.121
- Liu TP, Mobus B, Braybrook G (1989) Fine-structure of hypopharyngeal glands from honeybees with and without infestation by the tracheal mite, *Acarapis woodi* (Rennie). *Journal of Apicultural Research* 28:85-92.
- Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. *Bioscience* 56:311. doi:10.1641/0006-3568(2006)56[311:tevoes]2.0.co;2
- Losey JE, Vaughan M (2008) Conserving the ecological services provided by insects. *American Entomologist* 54:113-114.
- Lowenstein DM, Huseeth AS, Groves RL (2012) Response of wild bees (Hymenoptera: Apoidea: *Anthophila*) to surrounding land cover in Wisconsin pickling cucumber. *Environmental Entomology* 41:532-540. doi:10.1603/en11241
- Lowenstein DM, Matteson KC, Xiao I, Silva AM, Minor ES (2014) Humans, bees, and pollination services in the city: the case of Chicago, IL (USA). *Biodiversity and Conservation* 23:2857-2874. doi:10.1007/s10531-014-0752-0
- Lundin O, Rundlöf M, Smith HG, Fries I, Bommarco R (2015) Neonicotinoid insecticides and their impacts on bees: a systematic review of research approaches and identification of knowledge gaps. *PLoS One* 10:e0136928. doi:10.1371/journal.pone.0136928
- Lye G, Park K, Osborne J, Holland J, Goulson D (2009) Assessing the value of rural stewardship schemes for providing foraging resources and nesting habitat for bumblebee queens (Hymenoptera: Apidae). *Biological Conservation* 142:2023-2032. doi:10.1016/j.biocon.2009.03.032
- Lye GC, Jennings SN, Osborne JL, Goulson D (2011) Impacts of the use of nonnative commercial bumble bees for pollinator supplementation in raspberry. *Journal of Economic Entomology* 104:107-114. doi:10.1603/ec10092
- Macadam CR, Bairner SZ (2012) Urban biodiversity: successes and challenges: brownfields: oases of urban biodiversity. *Glasgow Naturalist* 25:29-32.
- Macfarlane RP (1976) Fungi associated with Bombinae (Apidae-Hymenoptera) in North America. *Mycopathologia* 59:41-42. doi:10.1007/bf00491203
- Macfarlane RP, Pattern KD, Royce LA, Wyatt BKW (1995a) Applied pollination in temperate areas. *Pollination of Cultivated Plants in the Tropics* 20-39.
- Macfarlane RP, Lipa JJ, Liu HJ (1995b) Bumble bee pathogens and internal enemies. *Bee World* 76:130-148.
- MacIvor JS, Cabral JM, Packer L (2014) Pollen specialization by solitary bees in an urban landscape. *Urban Ecosystems* 17:139-147. doi:10.1007/s11252-013-0321-4
- MacIvor JS, Packer L (2015) 'Bee hotels' as tools for native pollinator conservation: a premature verdict? *PLoS One* 10:e0122126. doi:10.1371/journal.pone.0122126
- MacIvor JS, Packer L (2016) The bees among us: modelling occupancy of solitary bees. *PLoS One* 11:e0164764. doi:10.1371/journal.pone.0164764

- MacKay PA, Knerer G (1979) Seasonal occurrence and abundance in a community of wild bees from an old field habitat in Southern Ontario. *The Canadian Entomologist* 111:367-376.
- Mackenzie KE, Winston ML (1984) Diversity and abundance of native bee pollinators on berry crops and natural vegetation in the lower Fraser valley, British Columbia. *The Canadian Entomologist* 116:965-974.
- Mackenzie KE, Averill AL (1995) Bee (Hymenoptera, Apoidea) diversity and abundance on cranberry in southeastern Massachusetts. *Annals of the Entomological Society of America* 88:334-341.
- MacKenzie KE, Javorek S (1997) The potential of alfalfa leafcutter bees (*Megachile rotundata* L.) as pollinators of cranberry (*Vaccinium macrocarpon* Aiton). *Seventh International Symposium on Pollination* 437:345-351.
- Mader E, Spivak M, Evans EC (2010) *Managing Alternative Pollinators: a Handbook for Beekeepers, Growers, and Conservationists*. Natural Resource, Agriculture, and Engineering Service, Ithaca, New York, USA.
- Maki DL, Wilson WT, Rubink WL, Vargas CJ (1987) Seasonal fluctuations in tracheal mite *Acarapis woodi* populations in honey bee colonies in Texas, Nebraska USA and Mexico. *American Bee Journal* 127:847-848.
- Mallinger RE, Gratton C, Diekötter T (2015) Species richness of wild bees, but not the use of managed honeybees, increases fruit set of a pollinator-dependent crop. *Journal of Applied Ecology* 52:323-330. doi:10.1111/1365-2664.12377
- Mänd M, Mänd R, Williams IH (2002) Bumblebees in the agricultural landscape of Estonia. *Agriculture, Ecosystems & Environment* 89:69-76. doi:10.1016/S0167-8809(01)00319-X
- Mandelik Y, Winfree R, Neeson T, Kremen C (2012) Complementary habitat use by wild bees in agro-natural landscapes. *Ecological Applications* 22:1535-1546. doi:10.1890/11-1299.1
- Manning R, Rutkay A, Eaton L, Dell B (2007) Lipid-enhanced pollen and lipid-reduced flour diets and their effect on the longevity of honey bees (*Apis mellifera* L.). *Australian Journal of Entomology* 46:251-257. doi:10.1111/J.1440-6055.2007.00598.X
- Manrique AJ, Soares AEE (2002). Start of africanized honey bee selection program for increased propolis production and its effect on honey production. *Interciencia* 27:312-316.
- Maori E, Paldi N, Shafir S, Kalev H, Tsur E, Glick E, Sela I (2009) IAPV, a bee-affecting virus associated with Colony Collapse Disorder can be silenced by dsRNA ingestion. *Insect Molecular Biology* 18:55-60. doi:10.1111/j.1365-2583.2009.00847.x.
- Marr C, Hillyer I (1968) Effect of light intensity on pollination and fertilization of field and greenhouse tomatoes. *American Society of Horticultural Science Proceedings* 92:526.
- Marini L, Quaranta M, Fontana P, Biesmeijer JC, Bommarco R (2012) Landscape context and elevation affect pollinator communities in intensive apple orchards. *Basic and Applied Ecology* 13:681-689. doi:10.1016/j.baae.2012.09.003
- Marshall EJP, West TM, Kleijn D (2006) Impacts of an agri-environment field margin prescription on the flora and fauna of arable farmland in different landscapes. *Agriculture, Ecosystems & Environment* 113:36-44. doi:10.1016/j.agee.2005.08.036

- Martin EC (1973) The use of bees for crop pollination. *American Bee Journal* 113:422-423.
- Martin SJ, Highfield AC, Brettell L, Villalobos EM, Budge GE, Powell M, Nikaido S, Schroeder DC (2012) Global honey bee viral landscape altered by a parasitic mite. *Science* 8:1304-1306. doi:10.1126/science.1220941
- Martins KT, Gonzalez A, Lechowicz MJ (2015) Pollination services are mediated by bee functional diversity and landscape context. *Agriculture, Ecosystems & Environment* 200:12-20. doi:10.1016/j.agee.2014.10.018
- Matheson A, Buchmann S, Toole CO, Westrich P, Williams I (1996) *The Conservation of bees*. Academic Press, London, UK.
- Matsuda K, Buckingham SD, Kleier D, Rauh JJ, Grauso M, Sattelle DB (2001) Neonicotinoids: insecticides acting on insect nicotinic acetylcholine receptors. *Trends in Pharmacological Sciences* 22:573-580. doi:10.1016/S0165-6147(00)01820-4
- Matsumoto T (2013) Reduction in homing flights in the honey bee *Apis mellifera* after a sublethal dose of neonicotinoid insecticides. *Bulletin of Insectology* 66:1-9.
- Matteson KC, Ascher JS, Langellotto GA (2008) Bee richness and abundance in New York city urban gardens. *Annals of the Entomological Society of America* 101:140-150. doi:10.1603/0013-8746(2008)101[140:braain]2.0.co;2
- Matteson KC, Langellotto GA (2010) Determinates of inner city butterfly and bee species richness. *Urban Ecosystems* 13:333-347. doi:10.1007/s11252-010-0122-y
- Matteson KC, Langellotto GA (2011) Small scale additions of native plants fail to increase beneficial insect richness in urban gardens. *Insect Conservation and Diversity* 4:89-98. doi:10.1111/j.1752-4598.2010.00103.x
- Matteson KC, Grace JB, Minor ES (2013) Direct and indirect effects of land use on floral resources and flower-visiting insects across an urban landscape. *Oikos* 122:682-694. doi:10.1111/j.1600-0706.2012.20229.x
- Mattila HR, Otis GW (2006a) Influence of pollen diet in spring on development of honey bee (Hymenoptera: Apidae) colonies. *Journal of Economic Entomology* 99:604-613. doi:10.1603/0022-0493-99.3.604
- Mattila HR, Otis GW (2006b) Effects of pollen availability and *Nosema* infection during the spring on division of labor and survival of worker honey bees (Hymenoptera: Apidae). *Environmental Entomology* 35:708-717. doi:10.1603/0046-225X-35.3.708
- Mattila HR, Otis GW (2007) Manipulating pollen supply in honey bee colonies during the fall does not affect the performance of winter bees. *The Canadian Entomologist* 139:554-563. doi:10.4039/n06-079
- Mawdsley JR, Humpert M (2016) Revised State Wildlife Action Plans Offer New Opportunities for Pollinator Conservation in the USA. *Natural Areas Journal* 36:453-457. doi:10.3375/043.036.0412
- Mayer DF, Johansen CA, Burgett DM (1986) *Bee Pollination of Tree Fruits*. Pacific Northwest Extension Publishing, Pullman, Washington, USA.
- Mayer DF, Johansen CA, Lunden JD (1989) Honey bee foraging behavior on ornamental crabapple pollenizers and commercial apple cultivars. *Hortscience* 24:510-512.

- Mayer DF, Patten KD, Macfarlane RP (1994) Pear pollination with managed bumble bee (Hymenoptera: Apidae) colonies. *Melanderia* 50:20-23.
- Mayer DF, Lunden JD (1997) A comparison of commercially managed bumblebees and honeybees (Hymenoptera: Apidae) for pollination of pears. *Seventh International Symposium on Pollination* 437: 283-287.
- Mayer DF, Kovacs G, Lunden JD (1998) Field and laboratory tests on the effects of cyhalothrin on adults of *Apis mellifera*, *Megachile rotundata* and *Nomia melanderi*. *Journal of Apicultural Research* 37:33-37.
- Mayer DF, Lunden JD (1999) Field and laboratory tests of the effects of fipronil on adult female bees of *Apis mellifera*, *Megachile rotundata* and *Nomia melanderi*. *Journal of Apicultural Research* 38:191-197.
- McElheran (1990) National varroa survey. pp.16-17 in *Proceedings of the Canadian Association of Professional Apiculturists*. January 21-23 1990. Winnipeg, Manitoba, Canada.
- McFrederick QS, LeBuhn G (2006) Are urban parks refuges for bumble bees *Bombus* spp. (Hymenoptera: Apidae)? *Biological Conservation* 129:372-382. doi:10.1016/j.biocon.2005.11.004
- McGregor SE (1976) *Insect Pollination of Cultivated Crop Plants*. United States Government Printing Office, Washington D.C., USA.
- McKinney ML, Lockwood JL (1999) Biotic homogenization: a few winners replacing many losers in the next mass extinction. *Trends in Ecology & Evolution* 14:450-453.
- McLellan AR (1974) Some effects of pollen traps on colonies of honey bees. *Journal of Apicultural Research* 13:143-148.
- McLeod K (2013) Native bee (Hymenoptera: Apiformes) response to ecological restoration in southern Ontario. MSc thesis. University of Waterloo, Waterloo, Ontario, Canada. [https://uwspace.uwaterloo.ca/bitstream/handle/10012/7945/McLeod\\_Kylie.pdf?sequence=1](https://uwspace.uwaterloo.ca/bitstream/handle/10012/7945/McLeod_Kylie.pdf?sequence=1).
- McMahon DP, Fürst MA, Caspar J, Theodorou P, Brown MJF, Paxton RJ (2015) A sting in the spit: widespread cross-infection of multiple RNA viruses across wild and managed bees. *Journal of Animal Ecology* 84:615-624. doi:10.1111/1365-2656.12345
- McMullan JB (2011) A scientific note: migration of tracheal mites (*Acarapis woodi*) to old winter honey bees. *Apidologie* 42:577-578. doi:10.1007/s13592-011-0058-0
- Meadows R (2011) Wild bees boost CA crops. *Frontiers in Ecology and the Environment* 9:312.
- Meindl GA, Ashman TL (2013). The effects of aluminum and nickel in nectar on the foraging behavior of bumblebees. *Environmental Pollution* 177:78-81. doi:10.1016/j.envpol.2013.02.017
- Mel'Nichenko AN, Nikiforova NV (1979) Improving the yield of greenhouse tomatoes by forced pollination of their flowers by bees. *Soviet Agricultural Sciences* 6:7-10.
- Melathopoulos AP, Winston ML, Whittington R, Higo H, Le Doux M (2000a) Field evaluation of neem and Canola oil for the selective control of the honey bee

- (Hymenoptera: Apidae) mite parasites *Varroa jacobsoni* (Acari: Varroidae) and *Acarapis woodi* (Acari: Tarsonemidae). *Journal of Economic Entomology* 93:559-567. doi:10.1603/0022-0493-93.3.559
- Melathopoulos AP, Winston ML, Whittington R, Smith T, Lindberg C, Mukai A, Moore M (2000b) Comparative laboratory toxicity of neem pesticides to honey bees (Hymenoptera: Apidae), their mite parasites *Varroa jacobsoni* (Acari: Varroidae) and *Acarapis woodi* (Acari: Tarsonemidae), and brood pathogens *Paenibacillus larvae* and *Ascophaera apis*. *Journal of Economic Entomology* 93:199-209.
- Melathopoulos AP, Tyedmers P, Cutler GC (2014) Contextualising pollination benefits: effect of insecticide and fungicide use on fruit set and weight from bee pollination in lowbush blueberry. *Annual Review of Applied Biology* 165:387-394. doi:10.1111/aab.12143
- Melathopoulos AP, Cutler GC, Tyedmers P (2015) Where is the value in valuing pollination ecosystem services to agriculture? *Ecological Economics* 109:59-70. doi:10.1016/j.ecolecon.2014.11.007
- Memmott J, Craze PG, Waser NM, Price MV (2007) Global warming and the disruption of plant-pollinator interactions. *Ecology Letters* 10:710-717. doi:10.1111/j.1461-0248.2007.01061.x
- Memmott J, Carvell C, Pywell RF, Craze PG (2010) The potential impact of global warming on the efficacy of field margins sown for the conservation of bumble bees. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365:2071-2079. doi:10.1098/rstb.2010.0015
- Metcalf CL, Flint WP, Metcalf RL (1962) *Destructive and Useful Insects: their Habits and Control*. McGraw-Hill Book Company
- Michaloud S, Wiebes JT, Berg CC (1988) The co-occurrence of two pollinating species of fig wasps and one species of fig. *Biological and Medical Sciences* 88:93-119.
- Michener CD (2004) *Bees of the World*. The John Hopkins University Press, Baltimore, Maryland, USA.
- Minckley RL, Roulston TH, Williams NM (2013) Resource assurance predicts specialist and generalist bee activity in drought. *Proceedings of the Royal Society B: Biological Sciences* 280:20122703. doi:10.1098/rspb.2012.2703
- Mineau P, McLaughlin A (1996) Conservation of biodiversity within Canadian agricultural landscapes: integrating habitat for wildlife. *Journal of Agricultural & Environmental Ethics* 9:93-113.
- Moeri OE, Lait CG, Kovacs E, Borden JH, Campbell M (2011) SuperBoost (R) synthetic brood pheromone enhances spring build-up of overwintered honey bee colonies. *Journal of Apicultural Research* 50:265-271. doi:10.3896/ibra.1.50.4.03
- Molet M, Chittka L, Stelzer RJ, Streit S, Raine NE (2008). Colony nutritional status modulates worker responses to foraging recruitment pheromone in the bumblebee *Bombus terrestris*. *Behavioral Ecology and Sociobiology* 62:1919-1926. doi:10.1007/s00265-008-0623-3
- Moller H (1996) Lessons for invasion theory from social insects. *Conservation Biology* 78:125-142.

- Morandin LA, Lavery TM, Kevan PG (2001a) Bumble bee (Hymenoptera: Apidae) activity and pollination levels in commercial tomato greenhouses. *Journal of Economic Entomology* 94:462-467. doi:10.1603/0022-0493-94.2.462
- Morandin LA, Lavery TM, Kevan PG (2001b) Effect of bumble bee (Hymenoptera: Apidae) pollination intensity on the quality of greenhouse tomatoes. *Journal of Economic Entomology* 94:172-179. doi:10.1603/0022-0493-94.1.172
- Morandin LA, Lavery TM, Kevan PG, Khosla S, Shipp L (2001c) Bumble bee (Hymenoptera: Apidae) activity and loss in commercial tomato greenhouses. *The Canadian Entomologist* 133:883-893. doi:10.4039/Ent133883-6
- Morandin LA, Lavery TM, Gegear RJ, Kevan PG (2002) Effect of greenhouse polyethylene covering on activity level and photo-response of bumble bees. *The Canadian Entomologist* 134:539-549. doi:10.4039/Ent134539-4
- Morandin LA, Winston ML (2003) Effects of novel pesticides on bumble bee (Hymenoptera: Apidae) colony health and foraging ability. *Environmental Entomology* 32:555-563. doi:10.1603/0046-225X-32.3.555
- Morandin LA, Winston ML (2005) Wild bee abundance and seed production in conventional, organic, and genetically modified canola. *Ecological Applications* 15:871-881. doi:10.1890/03-5271
- Morandin LA, Winston ML (2006) Pollinators provide economic incentive to preserve natural land in agroecosystems. *Agriculture, Ecosystems & Environment* 116:289-292. doi:10.1016/j.agee.2006.02.012
- Morandin LA, Winston ML, Abbott VA, Franklin MT (2007) Can pastureland increase wild bee abundance in agriculturally intense areas? *Basic and Applied Ecology* 8:117-124. doi:10.1016/j.baae.2006.06.003
- Morandin LA, Kremen C (2013a) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecological Applications* 23:829-839. doi:10.1890/12-1051.1
- Morandin LA, Kremen C (2013b) Bee preference for native versus exotic plants in restored agricultural hedgerows. *Restoration Ecology* 21:26-32. doi:10.1111/j.1526-100X.2012.00876.x
- Moretti M, Obrist MK, Duelli P (2004) Arthropod biodiversity after forest fires: winners and losers in the winter fire regime of the southern Alps. *Ecography* 27:173-186. doi:10.1111/j.0906-7590.2004.03660.x
- Moretti M, de Bello F, Roberts SPM, Potts SG (2009) Taxonomical vs. functional responses of bee communities to fire in two contrasting climatic regions. *Journal of Animal Ecology* 78:98-108. doi:10.1111/j.1365-2656.2008.01462.x
- Moroń D, Skórka P, Lenda M, Rozej-Pabijan E, Wantuch M, Kajzer-Bonk J, Celary W, Mielczarek LE, Tryjanowski P (2014) Railway embankments as new habitat for pollinators in an agricultural landscape. *PLoS One* 9:e101297. doi:10.1371/journal.pone.0101297
- Morris AJ, Hegarty J, Báldi A, Robijns T (2011) Setting aside farmland in Europe: the wider context. *Agriculture, Ecosystems & Environment* 143:1-2. doi:10.1016/j.agee.2011.07.013

- Morse RA, Calderone NW (2000) *The Value of Honey Bees as Pollinators of U.S. Crops in 2000*. United States Department of Agriculture, Ithaca, New York, USA.
- Morton HL, Moffett JO (1972) Ovicidal and larvicidal effects of certain herbicides on honey bees. *Environmental Entomology* 5:611-614.
- Mullin CA, Frazier M, Frazier JL, Ashcraft S, Simonds R, Pettis JS (2010) High levels of miticides and agrochemicals in North American apiaries: implications for honey bee health. *PLoS One* 5:e9754. doi:10.1371/journal.pone.0009754
- Murray TE, Fitzpatrick U, Byrne A, Fealy R, Brown MJF, Paxton RJ (2012) Local-scale factors structure wild bee communities in protected areas. *Journal of Applied Ecology* 49:998-1008. doi:10.1111/j.1365-2664.2012.02175.x
- Murray TE, Coffey MF, Kehoe E, Horgan FG (2013) Pathogen prevalence in commercially reared bumble bees and evidence of spillover in conspecific populations. *Biological Conservation* 159:269-276. doi:10.1016/j.biocon.2012.10.021
- Murrell DC, Shuel RW, Tomes DT (1982) Nectar production and floral characteristics in birdsfoot-trefoil (*Lotus corniculatus* L.). *Canadian Journal of Plant Science* 62:361-371.
- Mussen EC, Lopez JE, Peng CYS (2004) Effects of selected fungicides on growth and development of larval honey bees, *Apis mellifera* L. (Hymenoptera: Apidae). *Environmental Entomology* 33:1151-1154. doi:10.1603/0046-225X-33.5.1151
- Mussen EC (2008) Fungicides toxic to bees? *Apiculture News* 17:1-3.
- Mutinelli F (2014) Honey bee health regulation in Oceania and Australia. pp. 307-311 in *Bee Health and Veterinarians*. World Organization for Animal Health, Paris, France.
- Mutinelli F, Montarsi F, Federico G, Granato A, Ponti AM, Grandinetti G, Ferre N, Franco S, Duquesnes V, Riviere MP, et al. (2014) Detection of *Aethina tumida* Murray (Coleoptera: Nitidulidae.) in Italy: outbreaks and early reaction measures. *Journal of Apicultural Research* 53:569-575. doi:10.3896/Ibra.1.53.5.13
- Muz MN, Girisgin AO, Muz D, Aydin L (2010) Molecular detection of *Nosema ceranae* and *Nosema apis* infections in Turkish apiaries with collapsed colonies. *Journal of Apicultural Research* 49:342. doi:10.3896/ibra.1.49.4.09
- Nagai T, Inoue R (2004) Preparation and functional properties of water extract and alkaline extract of royal jelly. *Food Chemistry* 84:181-186. doi:10.1016/S0308-8146(03)00198-5
- Nakajima Y, Tsuruma K, Shimazawa M, Mishima S, Hara H (2009) Comparison of bee products based on assays of antioxidant capacities. *BMC Complementary and Alternative Medicine* 9:4. doi:10.1186/1472-6882-9-4
- Nardone E (2013) The bees of Algonquin Park: a study of their distribution, their community guild structure, and the use of various sampling techniques in logged and unlogged hardwood stands. MSc thesis, University of Guelph, Guelph, Ontario, Canada. <http://www.uoguelph.ca/canpolin/Publications/Nardone.pdf>
- Nason JD, Herre A, Hamrick JL (1998) The breeding structure of a tropical keystone plant resource. *Nature* 391:685-687.
- Nasr M, Kevan PG (1999) Diseases and parasites, eradication or management: what strategy for honey bee health? *Bee World* 80:53-54.

- Naug D (2009) Nutritional stress due to habitat loss may explain recent honeybee colony collapses. *Biological Conservation* 142:2369-2372. doi:10.1016/j.biocon.2009.04.007
- Naumann K, Currie RW, Isman MB (1994) Evaluation of the repellent effects of a neem insecticide on foraging honey bees and other pollinators. *The Canadian Entomologist* 126:225-230.
- Neame LA, Griswold T, Elle E (2012) Pollinator nesting guilds respond differently to urban habitat fragmentation in an oak-savannah ecosystem. *Insect Conservation and Diversity* 6:57-66. doi:10.1111/j.1752- 4598.2012.00187.x
- Neumann P, Elzen PJ (2004) The biology of the small hive beetle (*Aethina tumida*, Coleoptera: Nitidulidae): gaps in our knowledge of an invasive species. *Apidologie* 35:229-247. doi:10.1051/apido:2004010
- Neumann P, Hoffmann D, Duncan M, Spooner-Hart R (2010) High and rapid infestation of isolated commercial honey bee colonies with small hive beetles in Australia. *Journal of Apicultural Research* 49:343-344. doi:10.3896/Ibra.1.49.4.10
- Nentwig W (1998) Weedy plant species and their beneficial arthropods: potential for manipulation in field crops. pp. 49-72 in *Enhancing Biological Control: Habitat Management to Promote Natural Enemies of Agricultural Pests*. Eds. Berkeley CHP, Berkeley RLB. University of California Press, Oakland, California, USA.
- Nguyen BK, Saegerman C, Pirard C, Mignon J, Widart J, Thurionet B, Verheggen FJ, Berkvens D, de Pauw E, Haubruge E (2009) Does imidacloprid seed- treated maize have an impact on honey bee mortality? *Journal of Economic Entomology* 102:616-623.
- Nicholls CI, Altieri MA (2013) Plant biodiversity enhances bees and other insect pollinators in agroecosystems: a review. *Agronomy for Sustainable Development* 33:257-274. doi:10.1007/s13593-012-0092-y
- Nielsen A, Dauber J, Kunin WE, Lamborn E, Jauker B, Moora M, Potts SG, Reitan T, Roberts S, Sober V, et al. (2012) Pollinator community responses to the spatial population structure of wild plants: a pan-European approach. *Basic and Applied Ecology* 13:489-499. doi:10.1016/j.baae.2012.08.008
- Nielsen SL, Nicolaisen M, Kryger P (2008) Incidence of acute bee paralysis virus, black queen cell virus, chronic bee paralysis virus, deformed wing virus, kashmir bee virus and sacbrood virus in honey bees (*Apis mellifera*) in Denmark. *Apidologie* 39:310-314. doi:10.1051/apido:2008007
- Niemelä J, Kotze J, Ashworth A, Brandmayr P, Desender K, New T, Penev LD, Samways M, Spence J (2000) The search for common anthropogenic impacts on biodiversity: a global network. *Journal of Insect Conservation* 4:3-9. doi:10.1023/A:1009655127440
- Noordijk J, Raemakers IP, Schaffers AP, Sýkora KV (2009) Arthropod richness in roadside verges in the Netherlands. *Terrestrial Arthropod Reviews* 2:63-76. doi:10.1163/187498309X440085
- Nordström S, Faries I, Abarhus A, Hcansen H, Korpela K (1999) Virus infections in Nordic honey bee colonies with no, low or severe *Varroa jacobsoni* infestations. *Apidologie* 29:475-484.



- Nyeki J, Szabo Z, Benedek P, Szalay L (2002) Nectar production, honeybee visitation and fruit set of peach flowers. pp. 537-541 in *Proceedings of the Fifth International Peach Symposium*. International Society for Horticultural Science, Davis, California, USA.
- Olivero G (1994) Foraging bees on extrafloral nectaries of peach tree. *Apicoltore Moderno* 85:71-72.
- OBA Tech-Transfer (2004) 2005 OBA tech-transfer program research. Ontario Beekeepers Association, Guelph, Canada. <http://www.ontariobee.com/outreach/ttp/2005Research>.
- OBA Tech-Transfer Program (2013) 2013 OBA tech-transfer program research. Ontario Beekeepers Association, Guelph, Ontario, Canada. <http://www.ontariobee.com/outreach/ttp/2013Research>.
- Ochoa R, Pettis JS, Erbe E, Wergin WP (2005) Observations on the honey bee tracheal mite *Acarapis woodi* (Acari: Tarsonemidae) using low-temperature scanning electron microscopy. *Experimental and Applied Acarology* 35:239-249. doi:10.1007/s10493-004-5080-8.
- Öckinger E, Smith HG (2007) Semi-natural grasslands as population sources for pollinating insects in agricultural landscapes. *Journal of Applied Ecology* 44:50-59. doi:10.1111/j.1365-2664.2006.01250.x
- Oliver L (1988) Principles of weed threshold research. *Weed Technology* 2:398-403.
- Ollerton J, Winfree R, Tarrant S (2011) How many flowering plants are pollinated by animals? *Oikos* 120:321-326. doi:10.1111/j.1600-0706.2010.18644.x
- Ollerton J, Erenler H, Edwards M, Crockett R (2014) Extinctions of aculeate pollinators in Britain and the role of large-scale agricultural changes. *Science* 346:1360-1362. doi:10.1126/science.1257259
- Olwell P, Riibe L (2016) National Seed Strategy: Restoring Pollinator Habitat Begins with the Right Seed in the Right Place at the Right Time. *Natural Areas Journal* 36:363-365. doi:10.3375/043.036.0403
- OMAFRA (2012) An introduction to honey bee pests and diseases in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario Canada.
- OMAFRA (2013) Herbicides used in Ontario. In: Ontario Ministry of Agriculture Food & Rural Affairs, Guide to Weed Control, 2014-2015. Queen's Printer for Ontario, Toronto, Ontario, Canada. <http://www.omafra.gov.on.ca/english/crops/pub75/pub75ch11.pdf>
- OMAFRA (2014a) Number of active honey bee yards in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs, Resource Information and Business Services Unit, Environmental Management Branch, Guelph, Ontario, Canada. <http://www.omafra.gov.on.ca/english/about/beehealthpresentations/omafapiary.htm>
- OMAFRA (2014b) Pollinator health: a proposal for enhancing pollinator health and reducing the use of neonicotinoid pesticides in Ontario. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada. <http://www.omafra.gov.on.ca/english/pollinator/discuss-paper.htm>

OMAFRA (2016) Pollinator Health Action Plan. Ontario Ministry of Agriculture Food and Rural Affairs, Guelph, Ontario, Canada.

[http://www.omafra.gov.on.ca/english/pollinator/action\\_plan.htm](http://www.omafra.gov.on.ca/english/pollinator/action_plan.htm)

Osborne JL, Williams IH, Corbet SA (1991) Bees, pollination and habitat change in the European community. *Bee World* 72:99-116.

Osborne JL, Martin AP, Shortall CR, Todd AD, Goulson D, Knight ME, Hale RJ, Sanderson RA (2008) Quantifying and comparing bumblebee nest densities in gardens and countryside habitats. *Journal of Applied Ecology* 45:784-792. doi:10.1111/j.1365-2664.2007.01359.x

Ostermann DJ, Currie RW (2004) Effect of formic acid formulations on honey bee (Hymenoptera: Apidae) colonies and influence of colony and ambient conditions on formic acid concentration in the hive. *Journal of Economic Entomology* 97:1500-1508. doi:10.1603/0022-0493-97.5.1500

Otis GW, Bath JB, Randall DL, Grant GM (1988) Studies of the honey bee tracheal mite (*Acarapis woodi*) (Acari: tarsonemidae) during winter. *Canadian Journal of Zoology* 66:2122-2127.

Otis GW, Scott-Dupree CD (1992) Effects of *Acarapsis woodi* on overwintered colonies of honey bees (Hymenoptera, Apidae) in New York. *Journal of Economic Entomology* 85:40-46.

Otterstatter MC, Whidden TL (2004) Patterns of parasitism by tracheal mites (*Locustacarus buchneri*) in natural bumble bee populations. *Apidologie* 35:351-357. doi:10.1051/apido:2004024

Otterstatter MC, Gegear RJ, Colla SR, Thomson JD (2005) Effects of parasitic mites and protozoa on the flower consistency and foraging rate of bumble bees. *Behavioral Ecology and Sociobiology* 58:383-389. doi:10.1007/s00265-005-0945-3

Otterstatter MC, Thomson JD (2008) Does pathogen spillover from commercially reared bumble bees threaten wild pollinators? *PLoS One* 3:e2771. doi:10.1371/journal.pone.0002771

Otti O, Schmid-Hempel P (2007) *Nosema bombi*: a pollinator parasite with detrimental fitness effects. *Journal of Invertebrate Pathology* 96:118-24. doi:10.1016/j.jip.2007.03.016

Otto CR, Roth CL, Carlson BL, Smart MD (2016) Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. *Proceedings of the National Academy of Sciences of the United States of America* 113:10430-10435. doi:10.1073/pnas.1603481113

Ovaskainen O, Skorokhodova S, Yakovleva M, Sukhov A, Kutenkov A, Kutenkova N, Shcherbakov A, Meyke E, del Mar Delgado M (2013) Community-level phenological response to climate change. *Proceedings of the National Academy of Sciences of the United States of America* 110:13434-13439. doi:10.1073/pnas.1305533110

Owen EL, Bale JS, Hayward SA (2013) Can winter-active bumblebees survive the cold? Assessing the cold tolerance of *Bombus terrestris audax* and the effects of pollen feeding. *PLoS One* 8:e80061. doi:10.1371/journal.pone.0080061

- Packer L, Owen R (2001) Population genetic aspects of pollinator decline. *Conservation Ecology* 5:4.
- Page RE, Robinson GE, Fondrk MK, Nasr ME (1995) Effects of worker genotypic diversity on honey bee colony development and behaviour (*Apis mellifera* L.). *Behavioral Ecology and Sociobiology* 36:387-396. doi:10.1007/BF00177334
- Paimetova V, Mänd M, Kaufmane E, Libek A (2000) Pollinators of black currant (*Ribes nigrum* L.) and their pollination efficiency. pp. 164-167 in *Proceedings of the International Conference Fruit Production and Fruit Breeding, 12-13 September, 2000*. Estonian Agricultural University, Tartu, Estonia.
- Paini DR (2004) Impact of the introduced honey bee (*Apis mellifera*) (Hymenoptera: Apidae) on native bees: a review. *Austral Ecology* 29:399-407. doi:10.1111/J.1442-9993.2004.01376.X
- Paldi N, Glick E, Oliva M, Zilberberg Y, Aubin L, Pettis J, Chen Y, Evans JD (2010) Effective gene silencing of a microsporidian parasite associated with honey bee (*Apis mellifera*) colony declines. *Applied and Environmental Microbiology* 76:5960–5964. doi:10.1128/AEM.01067-10
- Palma G, Quezada-Euan JJG, Reyes-Oregel V, Melendez V, Moo-Valle H (2008) Production of greenhouse tomatoes (*Lycopersicon esculentum*) using *Nannotrigona perilampoides*, *Bombus impatiens* and mechanical vibration (Hymenoptera: Apoidea). *Journal of Applied Entomology* 132:79-85. doi:10.1111/j.1439-0418.2007.01246.x
- Palmer MJ, Moffat C, Saranzewa N, Harvey J, Wright GA, Connolly CN (2013) Cholinergic pesticides cause mushroom body neuronal inactivation in honeybees. *Nature Communications* 4:1634. doi:10.1038/ncomms2648 1634
- Parker FD, Torchio PF, Nye WP, Peterson M (1976) Utilization of additional species and populations of leafcutter bees for alfalfa pollination. *Journal of Apiculture Research* 15:89-92.
- Parker FD (1981) Sunflower pollination – abundance, diversity and seasonality of bees and their effect on seed yield. *Journal of Apicultural Research* 20:49-61.
- Parker FD, Batra SWT, Tepedino VJ (1987) New pollinators for our crops. *Agricultural Zoology Review* 2:279-304.
- Parker FD, Tepedino VJ (1990) Bee pollination of *Cuphea* (*Lythraceae*) species in greenhouse and field. *Pan-Pacific Entomologist* 66:9-12.
- Parker R, Melathopoulos AP, White R, Pernal SF, Guarna MM, Foster LJ (2010) Ecological adaptation of diverse honey bee (*Apis mellifera*) populations. *PLoS One* 5:e11096. doi:10.1371/journal.pone.0011096
- Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42. doi:10.1038/nature01286
- Parmesan C, Ryrholm N, Stefanescu C, Hill JK, Thomas CD, Descimon H, Huntley B, Kaila L, Kullberg J, Tammara T, et al. (2011) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399:579-583. doi:10.1038/21181

- Parsche S, Fründ J, Tschardt T (2011) Experimental environmental change and mutualistic vs. antagonistic plant flower-visitor interactions. *Perspectives in Plant Ecology Evolution and Systematics* 13:27-35. doi:10.1016/j.ppees.2010.12.001
- Patricio-Roberto GB, Campos MJO (2014) Aspects of landscape and pollinators-what is important to bee conservation? *Diversity* 6:158-175. doi:10.3390/d6010158
- Pătruică S, Mot D (2012) The effect of using prebiotic and probiotic products on intestinal micro-flora of the honeybee (*Apis mellifera carpatica*). *Bulletin of Entomological Research* 102:619-623. doi:10.1017/s0007485312000144
- Pavel CI, Mărghițaș LA, Bobiș O, Dezmișean DS, Șapcaliu A, Radoi I, Mădaș MN (2011) Biological activities of royal jelly-review. *Scientific Papers Animal Science and Biotechnologies* 44:108-118.
- Pavlik BM, Ferguson N, Nelson M (1993) Assessing limitations on the growth of endangered plant populations, II. Seed production and seed bank dynamics of *Erysimum capitatum* ssp. *Angustatum* and *Oenothera deltoids* spp. *Howellii*. *Biological Conservation* 65:267-278.
- Paxton RJ, Klee J, Korpela S, Fries I (2007) *Nosema ceranae* has infected *Apis mellifera* in Europe since at least 1998 and may be more virulent than *Nosema apis*. *Apidologie* 38:558-565. doi:10.1051/Apido:2007037
- Pe'er G, Dicks LV, Visconti P, Arlettaz R, Báldi A, Benton TG, Collins S, Dieterich M, Gregory RD, Hartig F, et al. (2014) EU agricultural reform fails on biodiversity. *Science* 344:1090-1092. doi:10.1126/science.1253425
- Pelletier L, McNeil JN (2003) The effect of food supplementation on reproductive success in bumblebee field colonies. *Oikos* 103:688-694. doi:10.1034/j.1600-0706.2003.12592.x
- Pelletier L, McNeil JN (2004) Do bumblebees always forage as much as they could? *Insectes Sociaux* 51:271-274. doi:10.1007/s00040-004-0748-y
- Pellissier L, Bråthen KA, Vittoz P, Yoccoz NG, Dubuis A, Meier ES, Zimmermann NE, Randin CF, Thuiller W, Garraud L, et al. (2013) Thermal niches are more conserved at cold than warm limits in arctic-alpine plant species. *Global Ecology and Biogeography* 22:933-941. doi:10.1111/geb.12057
- Pernal SF, Currie RW (2001) The influence of pollen quality on foraging behavior in honeybees (*Apis mellifera* L.). *Behavioral Ecology and Sociobiology* 51:53-68. doi:10.1007/S002650100412
- Petanidou T, Kallimanis AS, Sgardelis SP, Mazaris AD, Pantis JD, Waser NM (2014) Variable flowering phenology and pollinator use in a community suggest future phenological mismatch. *Acta Oecologica-International Journal of Ecology* 59:104-111. doi:10.1016/j.actao.2014.06.001
- Petchey OL, Gaston KJ (2006) Functional diversity: back to basics and looking forward. *Ecology Letters* 9:741-758. doi:10.1111/j.1461-0248.2006.00924.x
- Petersen JD, Huseeth AS, Nault BA (2014) Evaluating pollination deficits in pumpkin production in New York. *Environmental Entomology* 43:1247-1253. doi:10.1603/en14085

- Pettis JS, vanEngelsdorp D, Johnson J, Dively G (2012) Pesticide exposure in honey bees results in increased levels of the gut pathogen *Nosema*. *Naturwissenschaften* 99:153-158. doi:10.1007/s00114-011-0881-1
- Phillips S (2001) Fungicides and biocides. pp. 1109-1125 in *Clinical Environmental Health and Toxic Exposure* 2. Lippincott Williams and Wilkins, Philadelphia, Pennsylvania, USA.
- Piironen S, Botías C, Nicholls B, Goulson D (2016). No effect of low-level chronic neonicotinoid exposure on bumblebee learning and fecundity. *PeerJ* 4:e1808. doi:10.7717/peerj.1808
- Piironen S, Goulson D (2016). Chronic neonicotinoid pesticide exposure and parasite stress differentially affects learning in honeybees and bumblebees. *Proceedings of the Royal Society B: Biological Sciences* 283:20160246. doi:10.1098/rspb.2016.0246
- Pilling ED, Bromleychallenor KAC, Walker CH, Jepson PC (1995) Mechanism of synergism between the pyrethroid insecticide lambda-cyhalothrin and the imiazole fungicide prochloraz, in the honeybee (*Apis mellifera* L.). *Pesticide Biochemistry and Physiology* 51:1-11. doi:10.1006/pest.1995.1001
- Pilling E, Campbell P, Coulson M, Ruddle N, Tornier I (2013) A four-year field program investigating long-term effects of repeated exposure of honey bee colonies to flowering crops treated with thiamethoxam. *PLoS One* 8:e77193. doi:10.1371/journal.pone.0077193
- Pindar A, Packer L (in review) Fire disturbance organizes bee community and functional guild composition in an endangered ecosystem.
- Pisa LW, Amaral-Rogers V, Belzunces LP, Bonmatin JM, Downs CA, Goulson D, Kreutzweiser DP, Krupke C, Liess M, McField M, et al. (2015) Effects of neonicotinoids and fipronil on non-target invertebrates. *Environmental Science and Pollution Research* 22:68-102. doi:10.1007/s11356-014-3471-x
- Pitts-Singer TL, Bosch J, Kemp WP, Trostle GE (2008) Field use of an incubation box for improved emergence timing of *Osmia lignaria* populations used for orchard pollination. *Apidologie* 39:235-246. doi:10.1051/apido:2007061
- Pitts-Singer TL, Cane JH (2011) The alfalfa leafcutting bee, *Megachile rotundata*: the world's most intensively managed solitary bee. *Annual Review of Entomology* 56:221-237. doi:10.1146/annurev-ento-120709-144836
- Pitts-Singer TL, Cane JH, Trostle G (2014) Progeny of *Osmia lignaria* from distinct regions differ in developmental phenology and survival under a common thermal regime. *Journal of Insect Physiology* 67:9-19. doi:10.1016/j.jinsphys.2014.05.018
- Plowright RC, Hartling LK (1981) Red-clover pollination by bumble bees – a study of the dynamics of a plant-pollinator relationship. *Journal of Applied Ecology* 18:639-647. doi:10.2307/2402422
- PMRA (2014) Initiation of Special Reviews: Potential environmental risk related to *Peponapis pruinosa* exposure to Clothianidin, Imidacloprid and Thiamethoxam used on cucurbits. Pest Management Regulatory Agency: Health Canada. Ottawa; Canada.
- Polce C, Termansen M, Aguirre-Gutiérrez J, Boatman ND, Budge GE, Crowe A, Garratt MP, Pietravalle S, Potts SG, Ramirez JA, et al. (2013) Species distribution models for crop pollination: a modelling framework applied to great Britain. *PLoS One* 8:e76308. doi:10.1371/journal.pone.0076308

- Polce C, Garratt MP, Termansen M, Ramirez-Villegas J, Challinor AJ, Lappage MG, Boatman ND, Crowe A, Endalew AM, Potts SG, et al. (2014) Climate-driven spatial mismatches between British orchards and their pollinators: increased risks of pollination deficits. *Global Change Biology* 20:2815-2828. doi:10.1111/gcb.12577
- Polgar CA, Primack RB, Williams EH, Stichter S, Hitchcock C (2013) Climate effects on the flight period of Lycaenid butterflies in Massachusetts. *Biological Conservation* 160:25-31. doi:10.1016/j.biocon.2012.12.024
- Pontin DR, Wade MR, Kehrli P, Wratten SD (2006) Attractiveness of single and multiple species flower patches to beneficial insects in agroecosystems. *Annals of Applied Biology* 148:39-47. doi:10.1111/j.1744-7348.2005.00037.x
- Potts SG, Dafni A, Ne'eman G (2001) Pollination of a core flowering shrub species in Mediterranean phrygana: variation in pollinator diversity, abundance and effectiveness in response to fire. *Oikos* 92:71-80. doi:10.1034/j.1600-0706.2001.920109.x
- Potts SG, Vulliamy B, Dafni A, Ne'eman G, O'Toole C, Roberts S, Willmer P (2003) Response of plant-pollinator communities to fire: changes in diversity, abundance and floral reward structure. *Oikos* 101:103-112. doi:10.1034/j.1600-0706.2003.12186.x
- Potts SG, Petanidou T, Roberts S, O'Toole C, Hulbert A, Willmer P (2006) Plant- pollinator biodiversity and pollination services in a complex Mediterranean landscape. *Biological Conservation* 129:519-529. doi:10.1016/j.biocon.2005.11.019
- Potts SG, Woodcock BA, Roberts SPM, Tscheulin T, Pilgrim ES, Brown VK, Tallowin JR (2009) Enhancing pollinator biodiversity in intensive grasslands. *Journal of Applied Ecology* 46:369-379. doi:10.1111/j.1365/2009.01609.x
- Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution* 26:345-353. doi:10.1016/j.tree.2010.01.007
- Potts S, Biesmeijer JC, Bommarco R, Felicioli A, Fischer M, Jokinen P, Kleijn D, Klein A-M, Kunin WE, Neumann P, et al. (2011) Developing European conservation and mitigation tools for pollination services: approaches of the STEP (Status and Trends of European Pollinators) project. *Journal of Apicultural Research* 50:152-164. doi:10.3896/IBRA.1.50.2.07
- Potts SG, Imperatriz-Fonseca V, Ngo HT, Aizen MA, Biesmeijer JC, Breeze TD, Dicks LV, Garibaldi LA, Hill R, Settele J et al. (2016). Safeguarding pollinators and their values to human well-being. *Nature* 540:220-229. doi:10.1038/nature20588
- Prather CM, Pelini SL, Laws A, Rivest E, Woltz M, Bloch CP, Del Toro I, Ho C-K, Kominoski J, Newbold TAS, et al. (2013) Invertebrates, ecosystem services and climate change. *Biological Reviews* 88:327-348. doi:10.1111/brv.12002
- Primack RB (2006) Habitat Destruction. pp. 177-188 in *Essential of Conservation Biology* 4<sup>th</sup> ed. Sinauer Associates, Sunderland, Massachusetts, USA.
- Priore R, Sannino G (1981) Pollination of apricots cv. búlida by *Apis mellifera* L. *Fruits* 36:785-788.
- Pywell RF, Warman EA, Hulmes L, Hulmes S, Nuttall P, Sparks TH, Critchley CNR, Sherwood A (2006) Effectiveness of new agri-environment schemes in providing foraging

- resources for bumblebees in intensively farmed landscapes. *Biological Conservation* 129:192-206. doi:10.1016/j.biocon.2005.10.034
- Pywell RF, Meek WR, Loxton RG, Nowakowski M, Carvell C, Woodcock BA (2011) Ecological restoration on farmland can drive beneficial functional responses in plant and invertebrate communities. *Agriculture, Ecosystems & Environment* 140:62-67. doi:10.1016/j.agee.2010.11.012
- Pywell RF, Heard MS, Bradbury RB, Hinsley S, Nowakowski M, Walker KJ, Bullock JM (2012) Wildlife-friendly farming benefits rare birds, bees and plants. *Biology Letters* 8:772-775. doi:10.1098/rsbl.2012.0367
- Quaranta M, Ambroselli S, Barro P, Bella S, Carini A, Celli G, Cogoi P, Comba L, Bomoli R, Felicioli A, et al. (2004) Wild bees in agroecosystems and semi-natural landscapes. 1997-2000 collection period in Italy. *Bulletin of Insectology* 57:11-61.
- Rader R, Reilly J, Bartomeus I, Winfree R (2013) Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. *Global Change Biology* 19:3103-10. doi:10.1111/gcb.12264
- Rader R, Bartomeus I, Garibaldi LA, Garratt MPD, Howlett BG, Winfree R, Cunningham SA, Mayfield MM, Arthur AD, Andersson GKS et al. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences of the United States of America* 113:146-151. doi:10.1073/pnas.1517092112.
- Raine NE, Gill RJ (2015) Tasteless pesticides affect bees in the field. *Nature* 521:38-40. doi:10.1038/nature14391
- Rands SA, Whitney HM (2011) Field margins, foraging distances and their impacts on nesting pollinator success. *PLoS One* 6:e25971. doi:10.1371/journal.pone.0025971
- Rands SA (2014) Landscape fragmentation and pollinator movement within agricultural environments: a modelling framework for exploring foraging and movement ecology. *PeerJ* 2:e269. doi:10.7717/peerj.269
- Rasmont P, Iserbyt S (2012) The bumblebee scarcity syndrome: are heat waves leading to local extinctions of bumblebees (Hymenoptera: Apidae: *Bombus*)? *Annales de la Société Entomologique de France (NS)* 48:275-280. doi:10.1080/00379271.2012.10697776
- Rathcke BJ, Jules ES (1993) Habitat fragmentation and plant-pollinator interactions. *Pollination Biology in Tropics* 65:273-277.
- Ratti CM, Higo HA, Griswold TL, Winston ML (2008) Bumble bees influence berry size in commercial *Vaccinium* spp. cultivation in British Columbia. *The Canadian Entomologist* 140:348-363. doi:10.4039/n07-065
- Raw A (2000) Foraging behaviour of wild bees at hot pepper flowers (*Capsicum annuum*) and its possible influence on cross pollination. *Annals of Botany* 85:487-492.
- Redpath N, Osgathorpe LM, Park K, Goulson D (2010) Crofting and bumblebee conservation: the impact of land management practices on bumblebee populations in northwest Scotland. *Biological Conservation* 143:492-500. doi:10.1016/j.biocon.2009.11.019

- Redpath-Downing NA, Beaumont D, Park K, Goulson D (2013) Restoration and management of machair grassland for the conservation of bumblebees. *Journal of Insect Conservation* 17:491-502. doi:10.1007/s10841-012-9532-x
- Rennich K, Kunkel G, Abban S, Bozarth R, Eversole H, Evan J, Forsgren E, Levi V, Lopez D, Madella S, et al. (2013) 2012-2013 national honey bee pests and diseases survey report. USDA Animal and Plant Insepection Service, Maryland, USA.
- Richards KW (1984) Alfalfa leafcutter bee management in western Canada. Agriculture Canada, Ottawa, Ontario, Canada.
- Richards KW (1987) Alfalfa leafcutter management in Canada. *Bee World* 68:168-178.
- Richards KW, Whitfield GH, Schaalje GB (1987) Effects of temperature and duration of winter storage on survival and period of emergence for the alfalfa leafcutter bee (Hymenoptera: Megachilidae). *Journal of Kansas Entomological Society* 60:70-76.
- Richards KW (1997) Potential of the alfalfa leafcutter bee, *Megachile rotundata* (F.) (Hym., Megachilidae) to pollinate hairy and winter vetches (*Vicia* spp.). *Journal of Applied Entomology* 121:225-229.
- Richards KW (2003) Potential use of the alfalfa leafcutter bee *Megachile rotundata* to pollinate sweet clover. *Journal of Apicultural Research* 42:21-24. doi:10.1080/00218839.2003.11101082
- Richards MH, Rutgers-Kelly A, Gibbs J, Vickruck JL, Rehan SM, Sheffield CS (2011) Bee diversity in naturalizing patches of Carolinian grasslands in southern Ontario, Canada. *The Canadian Entomologist* 143:279-299. doi:10.4039/N11-010
- Ricketts TH (2004) Tropical forest fragments enhance pollinator activity in nearby coffee crops. *Conservation Biology* 18:1262-1271. doi:10.1111/j.1523-1739.2004.00227.x
- Ricketts TH, Daily GC, Ehrlich PR, Michener CD (2004) Economic value of tropical forest to coffee production. *Proceedings of the National Academy of Sciences of the United States of America* 101:12579-12582. doi:10.1073/pnas.0405147101
- Ricketts TH, Regetz J, Steffan-Dewenter I, Cunningham SA, Kremen C, Bogdanski A, Gemmill-Herren B, Greenleaf SS, Klein A-M, Mayfield MM, et al. (2008) Landscape effects on crop pollination services: are there general patterns? *Ecology Letters* 11:499-515. doi:10.1111/j.1461-0248.2008.01157.x
- Riessberger U, Crailsheim K (1997) Short-term effect of different weather conditions upon the behaviour of forager and nurse honey bees (*Apis mellifera carnica* Pollmann). *Apidologie* 28:411-426. doi:10.1051/apido:19970608
- Robinson WS, Fell RD (1981) Effect of honey bee foraging behaviours on delicious apple set. *Hortscience* 16:326-328.
- Rogers SR, Cajamarca P, Tarpy DR, Burrack HJ (2013) Honey bees and bumble bees respond differently to inter- and intra-specific encounters. *Apidologie* 44:621-629.
- Rogers SR, Tarpy DR, Burrack HJ (2013) Multiple criteria for evaluating pollinator performance in highbush blueberry (Ericales: Ericaceae) agroecosystems. *Environmental Entomology* 42:1201-1209. doi:10.1603/en12303
- Rogers SR, Tarpy DR, Burrack HJ (2014) Bee species diversity enhances productivity and stability in a perennial crop. *PLoS One* 9:e97307. doi:10.1371/journal.pone.0097307



- Root R (1973) Organization of a plant-arthropod association in simple and diverse habitats: fauna of collards (*Brassica oleracea*). *Ecological Monographs* 43: 95-120.
- Ropeik D (2002) *Risk*. Houghton Mifflin Company, New York, New York, USA.
- Roulston TH, Goodell K (2011) The role of resources and risks in regulating wild bee populations. *Annual Review of Entomology* 56:293-312. doi:10.1146/annurev-ento-120709-144802
- Rundlöf M, Nilsson H, Smith HG (2008) Interacting effects of farming practice and landscape context on bumblebees. *Biological Conservation* 141:417-426. doi:10.1016/j.biocon.2007.10.011
- Rundlöf M, Andersson GKS, Bommarco R, Fries I, Hederström V, Herbertsson L, Jonsson O, Klatt BK, Pedersen TR, Yourstone J, Smith HG (2015) Seed coating with a neonicotinoid insecticide negatively impacts wild bees. *Nature* 521:77-80. doi:10.1038/nature14414
- Russell C, Schultz CB (2009) Effects of grass-specific herbicides on butterflies: an experimental investigation to advance conservation efforts. *Journal of Insect Conservation* 14:53-63. doi:10.1007/s10841-009-9224-3
- Russell KN, Ikerd H, Droege S (2005) The potential conservation value of unmowed powerline strips for native bees. *Biological Conservation* 124:133-148. doi:10.1016/j.biocon.2005.01.022
- Russo L, DeBarros N, Yang S, Shea K, Mortensen D (2013) Supporting crop pollinators with floral resources: network-based phenological matching. *Ecology and Evolution* 3:3125-3140. doi:10.1002/ece3.703
- Rust RW, Mason CE, Erickson EH (1980) Wild bees on soybeans, *Glycine max*. *Environmental Entomology* 9:230-232.
- Rust RW, Torchio P (1991) Induction and incidence of *Ascosphaera* infections in the blue orchard bee, *Osmia lignaria propinqua* (Hymenoptera: Megachilidae). *Acta Horticulturae* 288:169-271.
- Rutgers-Kelly AC, Richards MH (2013) Effect of meadow regeneration on bee (Hymenoptera: Apoidea) abundance and diversity in southern Ontario, Canada. *The Canadian Entomologist* 145:655-67. doi:10.4039/tce.2013.42
- Sabara HA, Winston ML (2003) Managing honey bees (Hymenoptera: Apidae) for greenhouse tomato pollination. *Journal of Economic Entomology* 96:547-554. doi:10.1603/0022-0493-96.3.547
- Sachman-Ruiz B, Narváez-Padilla V, Reynaud E (2015). Commercial *Bombus impatiens* as reservoirs of emerging infectious diseases in central México. *Biological Invasions* 17:2043-2053. doi:10.1007/s10530-015-0859-6
- Sáez A, Sabatino M, Aizen M (2014) The floral diversity of field margins influences the richness and abundance of native flower visitors in sunflower fields. *Ecologia Austral* 24:94-102.
- Sadd BM, Barribeau SM (2013) Heterogeneity in infection outcome: lessons from a bumblebee-trypanosome system. *Parasite Immunology* 35:339-349. doi:10.1111/pim.12043

- Sammataro D, de Guzman L, George S, Ochoa R, Otis GW (2013) Standard methods for tracheal mites research. *Journal of Apicultural Research* 52:1-20. doi:10.3896/IBRA.1.52.4.20
- Samnegård U, Persson AS, Smith HG (2011) Gardens benefit bees and enhance pollination in intensively managed farmland. *Biological Conservation* 144:2602-2606. doi:10.1016/j.biocon.2011.07.008
- Sandilands A (2010) *Birds of Ontario: Habitat Requirements, Limiting Factors and Status*. UBS Press, Vancouver, British Columbia, Canada.
- Sandrock C, Tanadini LG, Pettis JS, Biesmeijer JC, Potts SG, Neumann P (2014) Sublethal neonicotinoid insecticide exposure reduces solitary bee reproductive success. *Agricultural and Forest Entomology* 16:119-28. doi:10.1111/afe.12041
- Sanford MT (1987) *Diseases and Pests of the Honey Bee*. The Institute of Food and Agricultural Sciences, Gainesville, Florida, USA.
- Sárosspataki M, Báldi A, Batáry P, Józán Z, Erdős S, Rédei T (2009) Factors affecting the structure of bee assemblages in extensively and intensively grazed grasslands in Hungary. *Community Ecology* 10:182-188. doi:10.1556/ComEc.10.2009.2.7
- Sattler T, Obrist MK, Duelli P, Moretti M (2011) Urban arthropod communities: added value or just a blend of surrounding biodiversity? *Landscape and Urban Planning* 103:347-361. doi:10.1016/j.landurbplan.2011.08.008
- Schaffer WM, Zeh DW, Buchmann SL, Kleinhans S, Schaffer MV, Antrim J (1983) Competition for nectar between introduced honey bees and native North American bees and ants. *Ecology* 64:564-577.
- Scheper J, Bommarco R, Holzschuh A, Potts SG, Riedinger V, Roberts SP, Rundlöf M, Smith HG, Steffan-Dewenter I, Wickens JB, Wickens VJ (2015) Local and landscape-level floral resources explain effects of wildflower strips on wild bees across four European countries. *Journal of Applied Ecology* 52:1165-1175. doi:10.1111/1365-2664.12479
- Schluter C, Punja Z (2000) Floral biology and seed production in cultivated North American ginseng (*Panax quinquefolius*). *Journal of the American Society of Horticultural Science* 125:567-575.
- Schmickl T, Crailsheim K (2002) How honeybees (*Apis mellifera* L.) change their broodcare behaviour in response to non-foraging conditions and poor pollen conditions. *Behavioral Ecology and Sociobiology* 51:415-25. doi:10.1007/s00265-002-0457-3
- Schmidt LS, Schmidt JO, Rao H, Wang WY, Xu LG (1995) Feeding preference and survival of young worker honeybees (Hymenoptera, Apidae) fed rape, sesame, and sunflower pollen. *Journal of Economic Entomology* 88:1591-1595.
- Schoener TW (1979) Generality of the size-distance relation in models of optimal foraging. *American Naturalist* 114:902-914.
- Scholer J, Krischik V (2014) Chronic exposure of imidacloprid and clothianidin reduce queen survival, foraging, and nectar storing in colonies of *Bombus impatiens*. *PLoS One* 9:e91573. doi:10.1371/journal.pone.0091573

- Schüepp C, Herzog F, Entling MH (2014) Disentangling multiple drivers of pollination in a landscape-scale experiment. *Proceedings of the Royal Society B: Biological Sciences*, 281: 20132667. doi:10.1098/rspb.2013.2667
- Schweiger O, Biesmeijer JC, Bommarco R, Hickler T, Hulme PE, Klotz S, Kuhn I, Moora M, Nielsen A, Ohlemüller R, et al. (2010) Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. *Biological Reviews* 85:777-795. doi:10.1111/j.1469-185X.2010.00125.x
- Scott-Dupree CD, Winston ML (1987) Wild bee pollinator diversity and abundance in orchard and uncultivated habitats in the Okanagan Valley, British Columbia. *The Canadian Entomologist* 119:735-745.
- Scott-Dupree CD (1988) Biology and management of wild bee and domesticated honey bee pollinators for tree fruit pollination. *Dissertation Abstracts International B Sciences and Engineering* 48:2197-2197.
- Scott-Dupree CD, Conroy L, Harris CR (2009) Impact of currently used or potentially useful insecticides for canola agroecosystems on *Bombus impatiens* (Hymenoptera: Apidae), *Megachile rotundata* (Hymenoptera: Megachilidae), and *Osmia lignaria* (Hymenoptera: Megachilidae). *Journal of Economic Entomology* 102:177-182. doi:10.1603/029.102.0125
- Seeley RH, Morse RA (1976) The nest of the honey bee (*Apis mellifera* L.). *Insectes Sociaux* 23:495-512.
- Sedivy C, Dorn S (2013) Towards a sustainable management of bees of the subgenus *Osmia* (Megachilidae; *Osmia*) as fruit tree pollinators. *Apidologie* 45:88-105. doi:10.1007/s13592-013-0231-8
- Sepp K, Mikk M, Mänd M, Truu J (2004) Bumblebee communities as an indicator for landscape monitoring in the agri-environmental programme. *Landscape and Urban Planning* 67:173-183. doi:10.1016/S0169-2046(03)00037-9
- Severson DW, Nordheim EV, Erickson EH (1987) Variation in nectar characteristics within soybean cultivars. *Journal of Apicultural Research* 26:156-164.
- Sgolastra F, Bosch J, Molowny-Horas R, Maini S, Kemp WP (2010) Effect of temperature regime on diapause intensity in an adult-wintering Hymenopteran with obligate diapause. *Journal of Insect Physiology* 56:185-194. doi:10.1016/j.jinsphys.2009.10.001
- Sgolastra F, Kemp WP, Buckner JS, Pitts-Singer TL, Maini S, Bosch J (2011) The long summer: pre-wintering temperatures affect metabolic expenditure and winter survival in a solitary bee. *Journal of Insect Physiology* 57:1651-1659. doi:10.1016/j.jinsphys.2011.08.017
- Shanks CH (1969) Pollination of raspberries by honey bees. *Journal of Apicultural Research* 8:19-21.
- Sheffield CS (2008) Summer bees for spring crops? Potential problems with *Megachile rotundata* (Fab.) (Hymenoptera: Megachilidae) as a pollinator of lowbush blueberry (Ericaceae). *Journal of the Kansas Entomological Society* 81:276-287.

- Sheffield CS, Westby SM, Smith RF, Kevan PG (2008a) Potential of bigleaf lupine for building and sustaining *Osmia lignaria* populations for pollination of apple. The Canadian Entomologist 140:589-599. doi:10.4039/n08-011
- Sheffield CS, Kevan PG, Westby SM, Smith RF (2008b) Diversity of cavity-nesting bees (Hymenoptera: Apoidea) within apple orchards and wild habitats in the Annapolis Valley, Nova Scotia, Canada. The Canadian Entomologist 140:235-249. doi:10.4039/n07-058
- Sheffield CS, Westby SM, Kevan PG, Smith RF (2008c) Winter management options for the orchard pollinator *Osmia lignaria* Say (Hymenoptera: Megachilidae) in Nova Scotia. Journal of the Entomological Society of Ontario 139:3-18.
- Sheffield CS, Dumesh S, Cheryomina M (2011) *Hylaeus punctatus* (Hymenoptera: Colletidae), a bee species new to Canada, with notes on other non-native species. Journal of Entomological Society of Ontario 142:29-43.
- Sheffield CS, Kevan PG, Pindar A, Packer L (2013a) Bee (Hymenoptera: Apoidea) diversity within apple orchards and old fields in the Annapolis Valley, Nova Scotia, Canada. The Canadian Entomologist 145:94-114. doi:10.4039/tce.2012.89
- Sheffield CS, Pindar A, Packer L, Kevan PG (2013b) The potential of cleptoparasitic bees as indicator taxa for assessing bee communities. Apidologie 44: 501-510. doi: 10.1007/s13592-013-0200-2
- Shipp JL, Whitfield GH, Papadopoulos AP (1994) Effectiveness of the bumble bee, *Bombus impatiens* CR (Hymenoptera, Apidae), as a pollinator of greenhouse sweetpepper. Scientia Horticulturae 57:29-39. doi:10.1016/0304-4238(94)90032-9
- Shukla AK, Vijayaraghavan MR, Chaudhry B (1998) *Biology of Pollen*. Ashish Publishing House, Totnes, Devon, UK.
- Shuler RE, Roulston TH, Farris GE (2005) Farming practices influence wild pollinator populations on squash and pumpkin. Journal of Economic Entomology 98:790-795.
- Simone-Finstrom M, Spivak M (2010) Propolis and bee health: the natural history and significance of resin use by honey bees. Apidologie 41:295-311. doi:10.1051/apido/2010016
- Simone-Finstrom M, Li-Byarlay H, Huang MH, Strand MK, Rueppell O, Tarpy DR (2016) Migratory management and environmental conditions affect lifespan and oxidative stress in honey bees. Scientific Reports 6:32023. doi:10.1038/srep32023
- Sinclair BJ, Ferguson LV, Salehipour-Shirazi G, MacMillan HA (2013) Cross-tolerance and cross-talk in the cold: relating low temperatures to desiccation and immune stress in insects. Integrative and Comparative Biology 53:545-556. doi:10.1093/icb/ict004
- Singh R, Levitt AL, Rajotte EG, Holmes EC, Ostiguy N, vanEngelsdorp D, Lipkin WI, Depamphilis CW, Toth AL, Cox-Foster DL (2010) RNA viruses in hymenopteran pollinators: evidence of inter-taxa virus transmission via pollen and potential impact on non-*Apis* hymenopteran species. PLoS One 5:e14357. doi:10.1371/journal.pone.0014357
- Sjodin NE, Bengtsson J, Ekblom B (2008) The influence of grazing intensity and landscape composition on the diversity and abundance of flower-visiting insects. Journal of Applied Ecology 45:763-772. doi:10.1111/j.1365-2664.2007.01443.x

- Skandalis DA, Richards MH, Sformo TS, Tattersall GJ (2011) Climate limitations on the distribution and phenology of a large carpenter bee, *Xylocopa virginica* (Hymenoptera: Apidae). Canadian Journal of Zoology 89:785-795. doi:10.1139/z11-051
- Small E (1997) Biodiversity priorities from the perspective of Canadian agriculture: ten commandments. Canadian Field-Naturalist 111:487-505.
- Smith J (1969) Some effects of crop background on populations of aphids and their natural enemies on brussels sprouts. Annals of Applied Biology 63:326-330.
- Smith AA, Bentley M, Reynolds HL (2013) Wild bees visiting cucumber on midwestern US organic farms benefit from near-farm semi-natural areas. Journal of Economic Entomology 106:97-106. doi:10.1603/ec12007
- Southwick EE, Southwick L (1992) Estimating the economic value of honey bees (Hymenoptera, Apidae) as agricultural pollinators in the United States. Journal of Economic Entomology 85:621-633.
- Spiewok S, Neumann P (2006) Infestation of commercial bumblebee (*Bombus impatiens*) field colonies by small hive beetles (*Aethina tumida*). Ecological Entomology 31:623-628. doi:10.1111/j.1365-2311.2006.00827.x
- Spiewok S, Duncan M, Spooner-Hart R, Pettis JS, Neumann P (2008) Small hive beetle, *Aethina tumida*, populations II: dispersal of small hive beetles. Apidologie 39:683-693. doi:10.1051/apido:2008054
- Stanghellini MS, Ambrose JT, Schultheis JR (1998) Seed production in watermelon: a comparison between two commercially available pollinators. Hortscience 33:28-30.
- Stanghellini MS, Ambrose JT, Schultheis JR (2000) Foraging pattern comparisons between two commercial pollinators on field-grown watermelon (*Citrullus lanatus* (Thunb.) Matsum. and Nakai). Hortscience 35:431-431.
- Stanghellini MS, Ambrose JT, Schultheis JR (2002) Diurnal activity, floral visitation, and pollen deposition by honey bees and bumble bees in field-grown cucumber and watermelon. Journal of Apicultural Research 41:27-34.
- Stanley CA, Pitts-Singer TL, Bosch J (2011) Influence of rough handling on *Osmia lignaria* (Hymenoptera: Megachilidae) nest establishment in commercial orchards. Journal of Economic Entomology 104:750-752. doi:10.1603/EC10406
- Stanley DA, Garratt MPD, Wickens JB, Wickens VJ, Potts SG, Raine NE (2015a). Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. Nature 528:548-550. doi:10.1038/nature16167
- Stanley DA, Gunning D, Stout JC (2013a) Pollinators and pollination of oilseed rape crops (*Brassica napus* L.) in Ireland: ecological and economic incentives for pollinator conservation. Journal of Insect Conservation 17:1181-1189. doi:10.1007/s10841-013-9599-z
- Stanley DA, Knight ME, Stout JC (2013b) Ecological variation in response to mass-flowering oilseed rape and surrounding landscape composition by members of a cryptic bumblebee complex. PLoS One 8:e65516. doi:10.1371/journal.pone.0065516
- Stanley DA, Raine NE (2016). Chronic exposure to a neonicotinoid pesticide alters the interactions between bumblebees and wild plants. Functional Ecology 30:1132-1139. doi:10.1111/1365-2435.12644.

- Stanley DA, Smith KE, Raine NE (2015b) Bumblebee learning and memory is impaired by chronic exposure to a neonicotinoid pesticide. *Scientific Reports* 5:16508. doi:10.1038/srep16508
- Stanley DA, Stout JC (2014) Pollinator sharing between mass-flowering oilseed rape and co-flowering wild plants: implications for wild plant pollination. *Plant Ecology* 215:315-325. doi:10.1007/s11258-014-0301-7
- Statistics Canada (2006) Snapshot of Canadian Agriculture. Ottawa, Ontario, Canada. <http://www.statcan.gc.ca/ca-ra2006/articles/snapshot-portrait-eng.htm>.
- Statistics Canada (2008) Area of fruit, berries and nuts, vegetables, sod, nursery and greenhouse products, by province (Census of Agriculture 1986 to 2006). Ottawa, Ontario, Canada. <http://www.statcan.gc.ca/tables-tableaux/sum-som/101/cst01/agrc31g-eng.htm>
- Statistics Canada (2010) Initial research results: settlements and dependable agricultural land in southern Ontario and Quebec, 2006. Ottawa, Ontario, Canada. <http://www.statcan.gc.ca/pub/16-002-x/2010001/article/11134/map-carte/map-carte002-eng.htm>
- Statistics Canada (2011) The Canadian population in 2011: population counts and growth. Ottawa, Ontario, Canada. <http://www12.statcan.ca/census-recensement/2011/as-sa/98-310-x/98-310-x2011001-eng.cfm>
- Statistics Canada (2012a) 2011 Census of agriculture. Ottawa, Ontario, Canada. <http://www.statcan.gc.ca/eng/ca2011/index>
- Statistics Canada (2012b) Number and area of census farms, Canada and the provinces, 1996, 2001, 2006 and 2011. Ottawa, Ontario, Canada. <http://www.omafra.gov.on.ca/english/stats/census/number.htm>
- Statistics Canada (2013) Statistical overview of the Canadian honey industry. Ottawa, Ontario, Canada. <http://www.agr.gc.ca/eng/industry-markets-and-trade/statistics-and-market-information/by-product-sector/horticulture/horticulture-canadian-industry/sector-reports/statistical-overview-of-the-canadian-honey-industry-2013/?id=1411739633587>.
- Statistics Canada (2014a) Total farm cash receipts by province (\$'000). Ottawa, Ontario, Canada. <http://www.omafra.gov.on.ca/english/stats/finance/crprov.htm>
- Statistics Canada (2014b) Production and value of honey annual CANSIM. Ottawa, Ontario, Canada. <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0010007&tabMode=dtaTable&srchLan=-1&p1=-1&p2=9>
- Statistics Canada (2014c) Demographic changes in Canadian agriculture. Ottawa, Ontario, Canada. <http://www.statcan.gc.ca/pub/96-325-x/2014001/article/11905-eng.htm>.
- Steffan-Dewenter I (1998) Wild bees in the agricultural landscape: habitat selection, succession, pollination and competition by honey bees. *Agrarökologie* 27:1-134.
- Steffan-Dewenter I, Tschardt T (1999) Effects of habitat isolation on pollinator communities and seed set. *Oecologia* 121:432-440. doi:10.1007/s004420050949
- Steffan-Dewenter I, Münzenberg U, Tschardt T (2001) Pollination, seed set and seed predation on a landscape scale. *Proceedings of the Royal Society B: Biological Sciences* 268:1685-1690. doi:10.1098/rspb.2001.1737

- Steffan-Dewenter I, Münzenberg U, Bürger C, Thies C, Tschardt T (2002) Scale-dependent effects of landscape context on three pollinator guilds. *Ecology* 83:1421-1432. doi:10.2307/3071954
- Steffan-Dewenter I (2003) Importance of habitat area and landscape context for species richness of bees and wasps in fragmented orchard meadows. *Conservation Biology* 17:1036-1044. doi:10.1046/j.1523-1739.2003.01575.x
- Steffan-Dewenter I, Kuhn A (2003) Honeybee foraging in differentially structured landscapes. *Proceedings of the Royal Society B: Biological Sciences* 270:569-575. doi:10.1098/rspb.2002.2292
- Steffan-Dewenter I, Westphal C (2008) The interplay of pollinator diversity, pollination services and landscape change. *Journal of Applied Ecology* 45:737-741. doi:10.1111/j.1365-2664.2008.01483.x
- Steinhauer AL (1970) Honey bee pollination of cucumbers in Maryland. *American Bee Journal* 110:12-13.
- Stepanović S, Antić N, Dakić I, Švabić-Vlahović M (2003) In vitro antimicrobial activity of propolis and synergism between propolis and antimicrobial drugs. *Microbiological Research* 158:353-357.
- Stephen WA (1969) Honey bees for cucumber pollination in the USA. *American Bee Journal* 110:132-133.
- Stimec J, Scott-Dupree CD, McAndrews JH (1997) Honey bee, *Apis mellifera*, pollen foraging in Southern Ontario. *Canadian Field-Naturalist* 111:454-456.
- Stout JC, Morales CL (2009) Ecological impacts of invasive alien species on bees. *Apidologie* 40:388-409. doi:10.1051/apido/2009023
- Stubbs CS, Drummond FA (1997) Blueberry and cranberry (*Vaccinium* spp.) pollination: a comparison of managed and native bee foraging behavior. *Acta Horticulturae* (Wageningen) 437:341-344.
- Stubbs CS, Drummond FA, Allard S (1997) Bee conservation and increasing *Osmia* spp. in Maine lowbush blueberry fields. *Northeastern Naturalist* 4:133-144.
- Stubbs CS, Drummond FA (2001) *Bombus impatiens* (Hymenoptera: Apidae): an alternative to *Apis mellifera* (Hymenoptera: Apidae) for lowbush blueberry pollination. *Journal of Economic Entomology* 94:609-616. doi:10.1603/0022-0493-94.3.609
- Sunday JM, Bates AE, Kearney MR, Colwell RK, Dulvy NK, Longino JT, Huey RB (2014) Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *Proceedings of the National Academy of Sciences of the United States of America* 111:5610-5615. doi:10.1073/pnas.1316145111
- Sydenham MAK, Eldegard K, Totland O (2014) Spatio-temporal variation in species assemblages in field edges: seasonally distinct responses of solitary bees to local habitat characteristics and landscape conditions. *Biodiversity and Conservation* 23:2393-2414. doi:10.1007/s10531-014-0729-z
- Szabo ND, Colla SR, Wagner DL, Gall LF, Kerr JT (2012) Do pathogen spillover, pesticide use, or habitat loss explain recent North American bumblebee declines? *Conservation Letters* 5:232-239. doi:10.1111/j.1755-263X.2012.00234.x

- Szalanski AL, Whitaker J, Tripodi AD, Cappy P (2013) Prevalence of *Nosema* from managed honey bee colonies in South Dakota and New York. *Journal of Agricultural and Urban Entomology* 29:99-104. doi:10.3954/jaue13-03.1
- Szklanowska K, Dabska B (1991) Use of honey bees to pollination of apple flowers (*Malus domestica* Borkh) in small isolators. *Pszczelnicze Zeszyty Naukowe* 35:97-102.
- Szymas B, Langowska A, Kazimierzczak-Baryczko M (2012) Histological structure of the midgut of honey bees (*Apis mellifera* L.) fed pollen substitutes fortified with probiotics. *Journal of Apicultural Science* 56:5-12. doi:10.2478/v10289-012-0001-2
- Taki H, Boone JW, Viana BF, Silva FO, Kevan PG, Sheffield CS (2004) Effect of shading on trap nest utilization by hole-nesting aculeate Hymenoptera. *The Canadian Entomologist* 136:889-891. doi:10.4039/n04-014
- Taki H, Okabe K, Yamaura Y, Matsuura T, Sueyoshi M, Makino SI, Maeto K (2010) Effects of landscape metrics on *Apis* and non-*Apis* pollinators and seed set in common buckwheat. *Basic and Applied Ecology* 11:594-602. doi:10.1016/j.baae.2010.08.004
- Tang J, Wice J, Thomas VG, Kevan PG (2007) Assessment of Canadian federal and provincial legislation to conserve native and managed pollinators. *International Journal of Biodiversity Science & Management* 3:46-55.
- Tanksley SD (1984) High rates of cross-pollination in chile pepper (Insect pollinators, foreign pollen contamination). *Hortscience* 19:580-582.
- Tapaszt Z, Forgach P, Bakonyi T, Rusvai M (2010) Occurrence of viral diseases of honey bee (*Apis mellifera* L.) in Hungarian apiaries. *Magyar Allatorvosok Lapja* 132:119-25.
- Tarpy DR (2003) Genetic diversity within honeybee colonies prevents severe infections and promotes colony growth. *Proceedings of the Royal Society B: Biological Sciences* 270:99-103. doi:10.1098/Rspb.2002.2199
- Tarpy DR, Summers J, Keller JJ (2007) Comparison of parasitic mites in Russian-Hybrid and Italian honey bee (Hymenoptera: Apidae) colonies across three different locations in North Carolina. *Journal of Economic Entomology* 100:258-266. doi:10.1603/0022-0493(2007)100[258:Copmir]2.0.Co;2
- Tarpy DR, vanEngelsdorp D, Pettis JS (2013) Genetic diversity affects colony survivorship in commercial honey bee colonies. *Naturwissenschaften* 100:723-728. doi:10.1007/s00114-013-1065-y
- Tarrant S, Ollerton J, Rahman ML, Tarrant J, McCollin D (2013) Grassland restoration on landfill sites in the east midlands, United Kingdom: an evaluation of floral resources and pollinating insects. *Restoration Ecology* 21:560-568. doi:10.1111/j.1526-100X.2012.00942.x
- Tasei JN, Lerin J, Ripault G (2000) Sub-lethal effects of imidacloprid on bumblebees, *Bombus terrestris* (Hymenoptera: Apidae), during a laboratory feeding test. *Pest Management Science* 56:784-788. doi:10.1002/1526-4998(200009)56:9<784::aid-ps208>3.0.co;2-t
- Taylor AN, Catling PM (2011) Bees and butterflies in burned and unburned alvar woodland: evidence for the importance of postfire succession to insect pollinator diversity in an imperiled ecosystem. *Canadian Field-Naturalist* 125:297-306.



- Taylor KS, Waller GD, Crowder LA (1987) Impairment of a classical conditioned-response of the honey bee (*Apis mellifera* L.) by sublethal doses of synthetic pyrethroid insecticides. *Apidologie* 18:243-252. doi:10.1051/apido:19870304
- Tepedino VJ (1981) The pollination efficiency of the squash bee (*Peponapis pruinosa*) and the honey bee (*Apis mellifera*) on summer squash (*Curcubita pepo*). *Journal of the Kansas Entomological Society* 54:359-377.
- Tepedino VJ, Torchio PF (1989) Influence of nest hole selection on sex ratio and progeny size in *Osmia lignaria propinqua* (Hymenoptera: Megachilidae). *Annual Review of the Entomological Society of America* 82:355-360.
- Tepedino VJ, Torchio PF (1994) Founding and usurping: equally efficient paths to nesting success in *Osmia lignaria propinqua* (Hymenoptera: Megachilidae). *Annual Review of the Entomological Society of America* 87:946-953.
- Tepedino VJ, Alston DG, Bradley BA, Toler TR, Griswold TL (2007) Orchard pollination in Capitol Reef National Park, Utah, USA. Honey bees or native bees? *Biodiversity and Conservation* 16:3083-3094. doi:10.1007/s10531-007-9164-8
- Terborgh J (1986) Keystone plant resources in the tropical forest. pp. 330-344 in *Conservation Biology, The Science Of Scarcity And Diversity*. Sinauer, Sunderland, Massachusetts, USA.
- Tew JE, Caron DM (1988) Measurements of cucumber and soybean pollination efficiency by honey bees hived in prototypic pollination unit. *Ohio Agricultural Research and Development Center Research Circular* 295:38-41.
- The World Bank Group (2015) Agricultural land (% of land area). Washington D.C., USA. <http://data.worldbank.org/indicator/AG.LND.AGRI.ZS>
- Thompson H, Wilkins S (2003) Assessment of the synergy and repellency of pyrethroid/fungicide mixtures. *Bulletin of Insectology* 56:131-134.
- Thompson HM, Levine SL, Doering J, Norman S, Manson P, Sutton P, von Mérey G (2014) Evaluating exposure and potential effects on honeybee brood (*Apis mellifera*) development using glyphosate as an example. *Integrated Environmental Assessment and Management* 10:463-470. doi:10.1002/ieam.1529
- Thomson D (2004) Competitive interactions between the invasive European honey bee and native bumble bees. *Ecology* 85:458-470. doi:10.1890/02-0626
- Thomson JD (2010) Flowering phenology, fruiting success and progressive deterioration of pollination in an early-flowering geophyte. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365:3187-3199. doi:10.1098/rstb.2010.0115
- Thorp RW (2012) Biodiversity of native bees and crop pollination with emphasis on California. pp. 526-537 in *Biodiversity in Agriculture: Domestication, Evolution, and Sustainability*. Eds. Gepts P, Famula TR, Bettinger RL, Brush SB, Damania AB, McGuire PE, et al. Cambridge University Press, Boston, Massachusetts, USA.
- Tilman D, Lehman C (2001) Human-caused environmental change: impacts on plant diversity and evolution. *Proceedings of the National Academy of Sciences of the United States of America* 98:5433-5440. doi:10.1073/pnas.091093198

- Tomizawa M, Casida JE (2005) Neonicotinoid insecticide toxicology: mechanisms of selective action. *Annual Review of Pharmacology and Toxicology* 45:247-268. doi:10.1146/Annurev.Pharmtox.45.120403.095930
- Tommasi D, Miro A, Higo HA, Winston ML (2004) Bee diversity and abundance in an urban setting. *The Canadian Entomologist* 136:851-869. doi:10.4039/n04-010
- Torchio PF (1976) Use of *Osmia lignaria* Say (Hymenoptera: Apoidea, Megachilidae) as a pollinator in an apple and prune orchard. *Journal of Kansas Entomological Society* 49:475-482.
- Torchio PF (1981) Field experiments with *Osmia lignaria propinqua* Cresson as a pollinator in almond orchards: II 1976 studies (Hymenoptera: Megachilidae). *Journal of Kansas Entomological Society* 54:824-836.
- Torchio PF (1982) Field experiments with the pollinator species, *Osmia lignaria propinqua* Cresson, in apple orchards: II, 1976 studies (Hymenoptera: Megachilidae). *Journal of the Kansas Entomological Society* 55:759-778.
- Torchio PF (1985) Field experiments with the pollinator species, *Osmia lignaria propinqua* Cresson, in apple orchards: 5 (1979-1980), methods of introducing bees, nesting success, seed counts, fruit yields (Hymenoptera: Megachilidae). *Journal of the Kansas Entomological Society* 58:448-464.
- Torchio PF (1991) Use of *Osmia lignaria propinqua* (Hymenoptera: Megachilidae) as a mobile pollinator of orchard crops. *Environmental Entomology* 20:590-596.
- Torchio PF (1992) Effects of spore dosage and temperature on pathogenic expressions of chalkbrood syndrome caused by *Ascosphaera torchioi* within larvae of *Osmia lignaria propinqua* (Hymenoptera: Megachilidae). *Environmental Entomology* 21:1086-1091.
- Torres-Ruiz A, Jones RW (2012) Comparison of the efficiency of the bumble bees *Bombus impatiens* and *Bombus ephippiatus* (Hymenoptera: Apidae) as pollinators of tomato in greenhouses. *Journal of Economic Entomology* 105:1871-1877. doi:10.1603/ec12171
- Traver BE, Williams MR, Fell RD (2012) Comparison of within hive sampling and seasonal activity of *Nosema ceranae* in honey bee colonies. *Journal of Invertebrate Pathology* 109:187-193. doi:10.1016/J.Jip.2011.11.001
- Traver BE, Fell RD (2015) A scientific note: survey for *Nosema* spp. in preserved *Apis* spp. *Apidologie* 46:194-196. doi:10.1007/S13592-014-0306-1
- Traveset A, Richardson DM (2006) Biological invasions as disruptors of plant reproductive mutualisms. *Trends in Ecology & Evolution* 21:208-216. doi:10.1016/J.Tree.2006.01.006
- Tropek R, Cerna I, Straka J, Kadlec T, Pech P, Tichanek F, Sebek P (2014) Restoration management of fly ash deposits crucially influence their conservation potential for terrestrial arthropods. *Ecological Engineering* 73:45-52. doi:10.1016/j.ecoleng.2014.09.011
- Troy A, Bagstad K (2009) Estimating ecosystem services in Southern Ontario. Prepared for the Ontario Ministry of Natural Resources, Southern Region Planning Unit, Peterborough, Ontario, Canada.  
<http://www.greeninfrastructureontario.org/sites/greeninfrastructureontario.org/files/MNR%20Report.pdf>

- Tscharntke T, Klein A-M, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity: ecosystem service management. *Ecology Letters* 8:857-874. doi:10.1111/j.1461-0248.2005.00782.x
- Tscheulin T, Neokosmidis L, Petanidou T, Settele J (2011) Influence of landscape context on the abundance and diversity of bees in Mediterranean olive groves. *Bulletin of Entomological Research* 101:557-564. doi:10.1017/s0007485311000149
- Tschumi M, Albrecht M, Entling M, Jacot K (2014) Targeted flower strips effectively promote natural enemies of aphids. *Landscape Management for Functional Biodiversity, IOBC-WPRS Bulletin* 100:131-135.
- Tuell JK, Ascher JS, Isaacs R (2009) Wild bees (Hymenoptera: Apoidea: Anthophila) of the Michigan highbush blueberry agroecosystem. *Annual Review of the Entomological Society of America* 102:275-287. doi:10.1603/008.102.0209
- Underwood RM, Currie RW (2003) The effects of temperature and dose of formic acid on treatment efficacy against *Varroa destructor* (Acari: Varroidae), a parasite of *Apis mellifera* (Hymenoptera: Apidae). *Experimental and Applied Acarology* 29:303-313. doi:10.1023/a:1025892906393
- Underwood RM, Currie RW (2004) Indoor winter fumigation of *Apis mellifera* (Hymenoptera: Apidae) colonies infested with *Varroa destructor* (Acari: Varroidae) with formic acid is a potential control alternative in northern climates. *Journal of Economic Entomology* 97:177-186. doi:10.1603/0022-0493-97.2.177
- Underwood RM, Currie RW (2005) Effect of concentration and exposure time on treatment efficacy against *Varroa* mites (Acari: Varroidae) during indoor winter fumigation of honey bees (Hymenoptera: Apidae) with formic acid. *Journal of Economic Entomology* 98:1802-1809.
- Underwood RM, Currie RW (2007) Effects of release pattern and room ventilation on survival of varroa mites and queens during indoor winter fumigation of honey bee colonies with formic acid. *The Canadian Entomologist* 139:881-893. doi:10.4039/n06-085
- UNPD (2006) World urbanization prospects: the 2005 revision. United Nations Population Division, Department of Economic and Social Affairs, New York, New York, USA. <http://www.un.org/esa/population/publications/WUP2005/2005wup.htm>
- USDA (2009) Pollinator biology and habitat. United States Department of Agriculture, Natural Resources Conservation Service, Washington D.C., USA. [http://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs144p2\\_015043.pdf](http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_015043.pdf)
- UTRCA (2011) Invasive non-native plants in the upper Thames River watershed. Upper Thames Conservation Authority, London, Ontario, Canada. <http://thamesriver.on.ca/wp-content/uploads/InvasiveSpecies/Invasive-plants.pdf>
- Vaissière BE, Malaboeuf F, Rodet G (1996) Viability of cantaloupe pollen carried by honeybees *Apis mellifera* varies with foraging behavior. *Naturwissenschaften* 83:84-86.
- Van Nuland ME, Haag EN, Bryant JAM, Read QD, Klein RN, Douglas MJ, Gorman CE, Greenwell TD, Busby MW, Collins J, et al. (2013) Fire promotes pollinator visitation: implications for ameliorating declines of pollination services. *PLoS One* 8:e79853. doi:10.1371/journal.pone.0079853

Vanbergen AJ (2014) Landscape alteration and habitat modification: impacts on plant–pollinator systems. *Current Opinion in Insect Science* 5:44-49. doi:10.1016/j.cois.2014.09.004

Vanbergen AJ, Baude M, Biesmeijer JC, Britton NF, Brown MJF, Brown M, Bryden J, Budge GE, Bull JC, Carvell C, et al. (2013) Threats to an ecosystem service: pressures on pollinators. *Frontiers in Ecology and the Environment* 11:251-259. doi:10.1890/120126

Vandame R, Belzunces LP (1998) Joint actions of deltamethrin and azole fungicides on honey bee thermoregulation. *Neuroscience Letters* 251:57-60. doi:10.1016/s0304-3940(98)00494-7

vanEngelsdorp D, Otis GW (2001a) The role of cuticular compounds in the resistance of honey bees (*Apis mellifera*) to tracheal mites (*Acarapis woodi*). *Experimental and Applied Acarology* 25:593-603. doi:10.1023/a:1014775827234

vanEngelsdorp D, Otis GW (2001b) Field evaluation of nine families of honey bees for resistance to tracheal mites. *The Canadian Entomologist* 133:793-803. doi:10.4039/Ent133793-6

vanEngelsdorp D, Evans JD, Saegerman C, Mullin C, Haubruge E, Nguyen BK, Frazier M, Frazier J, Cox-Foster D, Chen Y, et al. (2009) Colony collapse disorder: a descriptive study. *PLoS One* 4:e6481. doi:10.1371/journal.pone.0006481

vanEngelsdorp D, Meixner MD (2010) A historical review of managed honey bee populations in Europe and the United States and the factors that may affect them. *Journal of Invertebrate Pathology* 103:80-95. doi:10.1016/j.jip.2009.06.011

vanEngelsdorp D, Tarpay DR, Lengerich EJ, Pettis JS (2013) Idiopathic brood disease syndrome and queen events as precursors of colony mortality in migratory beekeeping operations in the eastern United States. *Preventive Veterinary Medicine* 108:225-233. doi:10.1016/j.prevetmed.2012.08.004

Vaudo AD, Patch HM, Mortensen DA, Grozinger CM, Tooker JF (2014) Bumble bees exhibit daily behavioral patterns in pollen foraging. *Arthropod-Plant Interactions* 8:273-283. doi:10.1007/s11829-014-9312-5

Vaughan M, Shepherd M, Kremen C, Hoffman Black S (2007) Farming for bees: guidelines for providing native bee habitat on farms. The Xerces Society for Invertebrate Conservation, Portland, Oregon, USA. [http://www.xerces.org/wp-content/uploads/2008/11/farming\\_for\\_bees\\_guidelines\\_xerces\\_society.pdf](http://www.xerces.org/wp-content/uploads/2008/11/farming_for_bees_guidelines_xerces_society.pdf)

Velthuis HHW, van Doorn A (2006) A century of advances in bumblebee domestication and the economic and environmental aspects of its commercialization for pollination. *Apidologie* 37:421-451. doi:10.1051/Apido:2006019

Verma LR, Mattu VK, Rana RS, Dulta PC, Veeresh GK, Mallik B, Viraktamath CA (1990) Foraging activity of *Apis cerana* F. and *Apis mellifera* L. on apple and plum bloom. pp. 747-748 in *Social Insects and the Environment*. Eds. Veeresh GK, Mallik B, Viraktamath CA. Eleventh International Congress of IUSII, Bangalore, India.

Vicens N, Bosch J (2000) Weather-dependent pollinator activity in an apple orchard, with special reference to *Osmia cornuta* and *Apis mellifera* (Hymenoptera: Megachilidae and Apidae). *Environmental Entomology* 29:413-420. doi:10.1603/0046-225X-29.3.413

- Vidau C, Diogon M, Aufauvre J, Fontbonne R, Vigues B, Brunet J-L, Texier C, Biron DG, Blot N, El Alaoui H, et al. (2011) Exposure to sublethal doses of fipronil and thiacloprid highly increases mortality of honeybees previously infected by *Nosema ceranae*. PLoS One 6:e21550. doi:10.1371/journal.pone.0021550
- Visscher PK (1980) Adaptations of honey bees (*Apis mellifera*) to problems of nest hygiene. Sociobiology 5:249-260.
- Vulliamy B, Potts SG, Willmer PG (2006) The effects of cattle grazing on plant-pollinator communities in a fragmented Mediterranean landscape. Oikos 114:529-543. doi:10.1111/j.2006.0030-1299.14004.x
- Wahl O, Ulm K (1983) Influence of pollen feeding and physiological condition on pesticide sensitivity of the honey bee *Apis mellifera carnica*. Oecologia 59:106-128. doi:10.1007/bf00388082
- Waite RJ, Brown B, Thomson H, Bew MH (2003) Control of American foulbrood by eradication of infected colonies. Apiacta 134-136.
- Walters K (2013) Data, data everywhere but we don't know what to think? Neonicotinoid insecticides and pollinators. Outlooks on Pest Management 24:151-155. doi:10.1564/v24\_aug\_02
- Walters SA (2005) Influence of honey bee pollination on triploid watermelon fruit set and quality. Hortscience 40:1118-1118.
- Walters SA, Taylor BH (2004) Influence of honey bees on pumpkin yields in Illinois. Hortscience 39:866-866.
- Walters SA, Schultheis JR (2009) Directionality of pollinator movements in watermelon plantings. Hortscience 44:49-52.
- Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389-395. doi:10.1038/416389a
- Wang DI, Moeller FE (1969) Histological comparisons of the development of hypopharyngeal glands in healthy and *Nosema* infected worker honey bees. Journal of Invertebrate Pathology 14:135-142.
- Watson JC, Wolf AT, Ascher JS (2011) Forested landscapes promote richness and abundance of native bees (Hymenoptera: Apoidea: Anthophila) in Wisconsin apple orchards. Environmental Entomology 40:621-632. doi:10.1603/en10231
- Webster TC, Thorp RW, Briggs D, Skinner J, Parisian T (1985) Effects of pollen traps on honey bee (Hymenoptera: Apidae) foraging and brood rearing during almond and prune pollination. Environmental Entomology 14:683-686.
- Weidenmüller A, Kleineidam C, Tautz J (2002) Collective control of nest climate parameters in bumblebee colonies. Animal Behaviour 63:1065-1071. doi:10.1006/anbe.2002.3020
- Welch A, Drummond F, Tewari S, Averill A, Burand JP (2009) Presence and prevalence of viruses in local and migratory honeybees (*Apis mellifera*) in Massachusetts. Applied and Environmental Microbiology 75:7862-7865. doi:10.1128/aem.01319-09

Westcott LC, Winston ML (1999) Chemical acaricides in *Apis mellifera* (Hymenoptera: Apidae) colonies; do they cause nonlethal effects? The Canadian Entomologist 131:363-371.

Westrich P (1997) The importance of rape (*Sinapis arvensis* L.) as a food resource of wild bees (Hymenoptera, Apidae). Schriftenreihe Bayerisches Landesamt fuer Umweltschutz 142:43-58.

Westphal C, Steffan-Dewenter I, Tscharnkte T (2003) Mass flowering crops enhance pollinator densities at a landscape scale. Ecology Letters 6:961-965. doi:10.1046/j.1461-0248.2003.00523.x

Wheeler MM, Robinson GE (2014) Diet-dependent gene expression in honey bees: honey vs. sucrose or high fructose corn syrup. Scientific Reports 4:5726. doi:10.1038/srep05726 5726

Wheelock MJ, O'Neal ME (2016) Insect pollinators in Iowa cornfields: community identification and trapping method analysis. PLoS One 11:e0143479. doi:10.1371/journal.pone.0143479

Wheelock MJ, Rey KP, O'Neal ME (2016) Defining the insect pollinator community found in Iowa corn and soybean fields: implications for pollinator conservation. Environmental Entomology 45:1099-106. doi:10.1093/ee/nvw087

White P, Kerr JT (2006) Contrasting spatial and temporal global change impacts on butterfly species richness during the 20th century. Ecography 29:908-918. doi:10.1111/j.2006.0906-7590.04685.x

Whitehorn PR, O'Connor S, Wackers FL, Goulson D (2012) Neonicotinoid pesticide reduces bumble bee colony growth and queen production. Science 336:351-352. doi:10.1126/science.1215025

Whittington R, Winston ML (2003a) Are bumble bee colonies in tomato greenhouses obtaining adequate nutrition? The Canadian Entomologist 135:883-892. doi:10.4039/n02-121

Whittington R, Winston ML (2003b) Effects of *Nosema bombi* and its treatment fumagillin on bumble bee (*Bombus occidentalis*) colonies. Journal of Invertebrate Pathology 84:54-58. doi:10.1016/s0022-2011(03)00123-x

Whittington R, Winston ML (2004) Comparison and examination of *Bombus occidentalis* and *Bombus impatiens* (Hymenoptera: Apidae) in tomato greenhouses. Journal of Economic Entomology 97:1384-1389. doi:10.1603/0022-0493-97.4.1384

Wiebes JT (1979) Coevolution of figs and their insect pollinators. Annual Review of Ecology and Systematics 10:1-12.

Wien HC, Riggs D (1997) Pollination and fruit set of pumpkins in growers' fields in New York's Capital District. Hortscience 32:462-462.

Williams GR, Shafer ABA, Rogers REL, Shutler D, Stewart DT (2008) First detection of *Nosema ceranae*, a microsporidian parasite of European honey bees (*Apis mellifera*), in Canada and central USA. Journal of Invertebrate Pathology 97:189-192. doi:10.1016/j.jip.2007.08.005

Williams GR, Rogers REL, Kalkstein AL, Taylor BA, Shutler D, Ostiguy N (2009) Deformed wing virus in western honey bees (*Apis mellifera*) from Atlantic Canada and

- the first description of an overtly-infected emerging queen. *Journal of Invertebrate Pathology* 101:77-79. doi:10.1016/j.jip.2009.01.004
- Williams GR, Shutler D, Rogers REL (2010) Effects at nearctic north-temperate latitudes of indoor versus outdoor overwintering on the microsporidium *Nosema ceranae* and western honey bees (*Apis mellifera*). *Journal of Invertebrate Pathology* 104:4-7. doi:10.1016/j.jip.2010.01.009
- Williams IH (1994) The dependence of crop production within the European Union on pollination by honey bees. *Agricultural Zoology Reviews* 6:229-257.
- Williams NM, Kremen C (2007) Resource distribution among habitats determines solitary bee offspring production in a mosaic landscape. *Ecological Applications* 17:910–921.
- Williams NM (2011) Restoration of nontarget species: bee communities and pollination function in riparian forests. *Restoration Ecology* 19:450-459. doi:10.1111/j.1526-100X.2010.00707.x
- Williams NM, Tepedino VJ (2003) Consistent mixing of near and distant resources in foraging bouts by the solitary mason bee *Osmia lignaria*. *Behavioral Ecology* 14:141-149. doi:10.1093/beheco/14.1.141
- Williams NM, Kremen C (2007) Resource distributions among habitats determine solitary bee offspring production in a mosaic landscape. *Ecological Applications* 17:910-921. doi:10.1890/06-0269
- Williams NM, Crone EE, Roulston TH, Minckley RL, Packer L, Potts SG (2010) Ecological and life-history traits predict bee species responses to environmental disturbances. *Biological Conservation* 143:2280-2291. doi:10.1016/j.biocon.2010.03.024
- Williams NM, Winfree R (2013) Local habitat characteristics but not landscape urbanization drive pollinator visitation and native plant pollination in forest remnants. *Biological Conservation* 160:10-18. doi:10.1016/j.biocon.2012.12.035
- Williams P (1986) Environmental change and the distribution of British bumblebees (*Bombus Latr.*). *Bee World* 67:50-60.
- Williams P (2005) Does specialization explain rarity and decline British bumblebees? A response to Goulson et al. *Biological Conservation* 122:33-43. doi:10.1016/.2004.06.019
- Williams P, Colla S, Xie Z (2009) Bumblebee vulnerability: common correlates of winners and losers across three continents. *Conservation Biology* 23:931-940. doi:10.1111/j.1523-1739.2009.01176.x
- Williams PH, Osborne JL (2009) Bumblebee vulnerability and conservation world-wide. *Apidologie* 40:367-87. doi:10.1051/apido/2009025
- Williams RR, Brain P (1985) Honeybee activity when visiting flowers of the apple cultivars coxs orange pippin and golden delicious. *Journal of Horticultural Science* 60:25-28.
- Williamson SM, Willis SJ, Wright GA (2014) Exposure to neonicotinoids influences the motor function of adult worker honeybees. *Ecotoxicology* 23:1409-1418. doi:10.1007/s10646-014-1283-x

- Willis DS, Kevan P (1995) Foraging dynamics of *Peponapis pruinosa* (Hymenoptera: Anthophoridae) on pumpkin (*Curcubita pepo*) in southern Ontario. *The Canadian Entomologist* 127:167-175.
- Wilson RJ, Gutierrez D, Gutierrez J, Martinez D, Agudo R, Monserrat VJ (2005) Changes to the elevational limits and extent of species ranges associated with climate change. *Ecology Letters* 8:1138-1146. doi:10.1111/j.1461-0248.2005.00824.x
- Wilson WT, Maki DL, Vargas-C J, Cox RL, Rubink WL (1988) Honey bee swarm frequency and tracheal mite infection levels in bait hives along USA-Mexico border. *American Bee Journal* 128:811-812.
- Winfree R, Williams NM, Dushoff J, Kremen C (2007a) Native bees provide insurance against ongoing honey bee losses. *Ecology Letters* 10:1105-1113. doi:10.1111/j.1461-0248.2007.01110.x
- Winfree R, Williams NM, Dushoff J, Kremen C (2007b) Wild bees provide insurance against ongoing honey bee losses. *Ecological Society of America Annual Meeting Abstracts*, San Jose, California. USA. <http://esameetings.allenpress.com/2007/P8386.HTM>
- Winfree R (2008) Pollinator-dependent crops: an increasingly risky business. *Current Biology* 18:R968-R969. doi:10.1016/j.cub.2008.09.010
- Winfree R, Williams NM, Gaines H, Ascher JS, Kremen C (2008) Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA. *Journal of Applied Ecology* 45:793-802. doi:10.1111/j.1365-2664.2007.01418.x
- Winfree R, Aguilar R, Vázquez DP, LeBuhn G, Aizen MA (2009) A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology* 90:2068-2076. doi:10.1890/08-1245.1
- Winfree R, Kremen C (2009) Are ecosystem services stabilized by differences among species? A test using crop pollination. *Proceedings of the Royal Society B: Biological Sciences* 276:229-237. doi:10.1098/rspb.2008.0709
- Winfree R (2010) The conservation and restoration of wild bees. *Annals of the New York Academy of Sciences* 1195:169-197. doi:10.1111/j.1749-6632.2010.05449.x
- Winfree R, Bartomeus I, Cariveau DP (2011) Native pollinators in anthropogenic habitats. *Annual Review of Ecology, Evolution, and Systematics* 42:1-22. doi:10.1146/annurev-ecolsys-102710-145042
- Winfree R, Gross BJ, Kremen C (2011) Valuing pollination services to agriculture. *Ecological Economics* 71:80-88. doi:10.1016/j.ecolecon.2011.08.001
- Wojcik VA, McBride JR (2012) Common factors influence bee foraging in urban and wildland landscapes. *Urban Ecosystems* 15:581-598. doi:10.1007/s11252-011-0211-6
- Wojcik VA, Buchmann S (2012) Pollinator conservation and management on electrical transmission and roadside rights-of-way: a review. *Journal of Pollination Ecology* 7:16-26.
- Wood TJ, Holland JM, Hughes WO, Goulson D (2015) Targeted agri-environment schemes significantly improve the population size of common farmland bumblebee species. *Molecular Ecology* 24:1668-1680. doi:10.1111/mec.1314



- Woodcock BA, Isaac NJ, Bullock JM, Roy DB, Garthwaite DG, Crowe A, Pywell RF (2016) Impacts of neonicotinoid use on long-term population changes in wild bees in England. *Nature Communications* 7:12459. doi:10.1038/ncomms12459
- Woodcock TS (2012) Pollination in the agricultural landscape: best management practices for crop pollination. University of Guelph: Canadian Pollination Initiative (NSERC-CANPOLIN).  
[http://www.pollinator.ca/bestpractices/images/Pollination%20in%20Agricultural%20Landscape\\_Woodcock\\_Final.pdf](http://www.pollinator.ca/bestpractices/images/Pollination%20in%20Agricultural%20Landscape_Woodcock_Final.pdf)
- Woodward SL, Quinn JA (2011) *Encyclopedia of Invasive Species*. Greenwood Publishing Group, Santa Barbara, California, USA.
- Woteki C (2013) The road to pollinator health. *Science* 341:695-695. doi:10.1126/science.1244271
- Wright IR, Roberts SPM, Collins BE (2015) Evidence of forage distance limitations for small bees (Hymenoptera: Apidae). *European Journal of Entomology* 112:303-310. doi:10.14411/eje.2015.028
- Wray JC, Neame LA, Elle E (2014) Floral resources, body size, and surrounding landscape influence bee community assemblages in oak-savannah fragments. *Ecological Entomology* 39:83-93. doi:10.1111/een.12070
- Wray JC, Elle E (2015) Flowering phenology and nesting resources influence pollinator community composition in a fragmented ecosystem. *Landscape Ecology* 30:261-272. doi:10.1007/s10980-014-0121-0
- Xing HJ, Wang JT, Li JL, Fan ZT, Wang M, Xu SW (2010) Effects of atrazine and chlorpyrifos on acetylcholinesterase and carboxylesterase in brain and muscle of common carp. *Environmental Toxicology and Pharmacology* 30:26-30. doi:10.1016/J.Etap.2010.03.009
- Yoder JA, Jajack AJ, Cornacchione WS, Dunn AL, Cunningham EG, Matchett CL, Rosselot AE (2014) In vitro evaluation of sugar syrups, antibiotics, and miticides on growth of honey bee pathogen, *Ascosphaera apis*: emphasis for chalkbrood prevention is on keeping bees healthy. *Apidologie* 45:568-578. doi:10.1007/s13592-014-0274-5
- Yoneda M, Furuta H, Tsuchida K, Okabe K, Goka K (2008) Commercial colonies of *Bombus terrestris* (Hymenoptera: Apidae) are reservoirs of the tracheal mite *Locustacarus buchneri* (Acari: Podapolipidae). *Applied Entomology and Zoology* 43:73-76. doi:10.1303/aez.2008.73
- Yourth CP, Schmid-Hempel P (2006) Serial passage of the parasite *Crithidia bombi* within a colony of its host, *Bombus terrestris*, reduces success in unrelated hosts. *Proceedings of the Royal Society B: Biological Sciences* 273:655-659. doi:10.1098/rspb.2005.3371
- Youssef NN, McManus WR, Torchio PF (1985) Cross-infectivity potential of *Ascosphaera* spp. (Ascomycetes: *Ascosphaera*) on the bee, *Osmia lignaria propinqua* Cresson (Megachilidae: Osmia). *Journal of Economic Entomology* 78:227-231.
- Zayed A (2009) Bee genetics and conservation. *Apidologie* 40:237-262. doi:10.1051/apido/2009026

Zurbuchen A, Cheesman S, Klaiber J, Müller A, Hein S, Dorn S (2010a) Long foraging distances impose high costs on offspring production in solitary bees. *Journal of Animal Ecology* 79:674-681. doi:10.1111/j.1365-2656.2010.01675.x

Zurbuchen A, Landert L, Klaiber J, Müller A, Hein S, Dorn S (2010b) Maximum foraging ranges in solitary bees: only few individuals have the capability to cover long foraging distances. *Biological Conservation* 143:669-676. doi:10.1016/j.biocon.2009.12.003

## Appendix A. Search Terms and Keywords for Literature Search

The number of studies found in systematic literature search for Honey bee OR honey bee OR *Apis mellifera*; Wild bees OR native bees OR bees; hummingbird OR ruby throated hummingbird AND Ontario; wasp OR vespidae OR sphecidae OR pompilidae AND Ontario; butterfly OR butterflies OR moth OR lepidoptera AND Ontario; beetle OR beetles OR coleoptera AND Ontario; fly OR flies OR diptera AND Ontario. Key terms searched in each stress factor, the number of studies found, number of studies after duplicates were removed and the total number of studies that were relevant to Ontario are indicated. Literature search was completed using Web of Science and cross reference with Google Scholar. Searched 'all years', 'all publications types', no limits.

Climate	Climate	Agrochemicals	agrochemical
	Climate change		pesticide
Land Use Change	Weather		pyrethroid
	Winter		diamide
	Wintering loss		organophosphate
	OR winter loss		miticide
	Global warming		thymol
	Phenology shift		oxalic acid
	Land use change		sucroside
	Habitat loss		amitraz
	Agriculture		fluvalinate
	Fragmentation		fenproximate
	Degradation		hivastan
	Restoration		formic acid
	Urbanization		fungicide
	Modification		herbicide
	Farmining		insecticide
	practice		neonicotinoid
	Agricultural		clothianidin
	Intensification		imidacloprid
	Habitat alteration		thiamethoxam
	Human		sulfoxaflor
	disturbance		thiacloprid
	Modern farming		acetamiprid
			fipronil
			adjuvant
			seed treatment
			seed coating
			coformulation
			OR co-
			formulation
			tank mix OR
			tank-mix OR
			tankmix
			antibiotic

Pest and Pathogens	virus
	european
	foulbrood
	american
	foulbrood
	paenibacillus
	varroa
	small hive beetle
	aethina tumida
	deformed wing
	virus
	sacbrood virus
	OR sac brood
	virus
	iflavirus
	israeli acute
	paralysis virus
	kashmir bee virus
	aparavirus
	black queen cell
	virus
	cripavirus
	ascosphaera apis
	chalkbrood
	nosema
	tracheal mite
	acarapis woodi
	wax moth
	galleria
	mellonella
	achroia grisella
	bacteria
	acute bee
	paralysis virus
	chronic bee
	paralysis virus
	kakugo virus
	dicistrovirus
	gut parasite
	intestinal
	protozoa
	pathogen
	pest
Catch	loss
	decline
	death
	decrease
	community change

Management practices	migratory
	beekeeping
	shipping
	transportation
	management
	practice
	supplement
	indoor
	wrap
	monoculture
	greenhouse
	biobest
	equipment
	hygiene
	stock
Conservation strategies	import
	export
	split
	rent
	placement
	pollination
	service
	strategy
	conservation
	protection
	conservation
	strateg*
	conservation
	assessment
	conservation plan
	conservation
	evaluation
	conservation
	value
	reserve selection
	area selection
	priority area
	area identification
	bioregional
	conservation
	bioregional
	planning
	ecoregional
	assessment
	ecoregional
	conservation
	integrated
	conservation

	<p> natural area  identification  ecosystem service  ecosystem  function  environmental  service  environmental  function  ecological value  ecological service  ecological  function  ecosystem value  agri-environment  scheme  agri-environment  strateg*  integrated pest  management  integrated  farming  management  government  parliament  congress  action plan  nonprofit  organization OR  not-for-profit  organization  non government  organization OR  non-  governmental  organization  policy  management  enhancement  naturalization  biodiversity  body length  foraging distance  trap nest  translocation  experiment  rarity  threat </p>	<p> ecological role  nesting sites  farm bill  incentive  initiative  legislation  international  pollinator  initiative  integrated  conservation  in situ  conservation  ex situ  conservation  rights of way  evaluation  adaptive  management  natural resource  management  resilience </p>
Crop pollination		<p> Cucumber or  Cucumis sativus  Melon OR  Cucumis melo  Watermelon OR  Citrullus lanatus  Squash OR  Pumpkins or  Zucchini or  Cucurbita  Peas OR Pisum  sativum  Green Bean OR  Phaseolus  Broad Bean OR  Vicia faba  Field Tomato OR  Lycopersicon  esculentum  Pepper OR  Capsicum  annuum  Apple OR Malus  domestica  Pear OR Pyrus  communis  Plum OR Prunus </p>

Sweet Cherry OR  
 Prunus avium  
 Sour Cherry OR  
 Prunus cerasus  
 Apricot OR  
 Prunus armeniaca  
 Peach OR  
 Nectarine or  
 Prunus persica  
 Currant OR  
 Gooseberry or  
 Ribes  
 Raspberry OR  
 Blackberry or  
 Rubus  
 Strawberry OR  
 Fragaria ananassa  
 Highbush  
 blueberry OR  
 Vaccinium  
 corymbosum  
 Cranberry OR  
 Vaccinium  
 macrocarpon  
 Alfalfa OR  
 Medicago sativa  
 Clover OF  
 Trifolium  
 Crown vetch OR  
 Coronilla varia  
 Birdsfoot-Trefoil  
 OR Lotus  
 corniculatus  
 Lupine OR  
 Lupinus  
 Canola OR  
 Brassica  
 Sunflower OR  
 Helianthus annus  
 Soybean OR  
 Glycine max  
 Peanut OR  
 Arachis hypogaea  
 Tomato OR  
 Lycopersicon  
 esculentum  
 Pepper OR  
 Capsicum  
 annum

American  
 Ginseng OR  
 Panax  
 quinquefolius  
 Buckwheat OR  
 Fagopyrum  
 esculentum  
 agriculture  
 contribution  
 biodiversity  
 mass flowering  
 crop  
 ecosystem service  
 pollination  
 service  
 foraging  
 foraging distance  
 agro environment  
 scheme  
 nesting sites  
 resilience  
 crop pollination  
 AND Ontario  
 redundancy