Pollination in the Agricultural Landscape

Best Management Practices for Crop Pollination

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1.0 Introduction

1.1 Pollination Basics

Pollination is the term given to the process of sexual reproduction in plants, in which a male sexual cell, the pollen grain (actually a group of cells called a *gametophyte*) is transferred to a female flower of the same species, germinates on the receptive stigma, and subsequently fertilizes the female gametophyte (*ovule*). All of these steps must occur in order for pollination to have taken place, and in the case of agricultural production, for the marketable commodity, an edible seed or fruit, to have a chance of developing. As in all sexually reproducing organisms, mating results in offspring that share genetic material with both parents, and form the next generation of plants. Unlike animals, however, plants must remain in a single place, and therefore rely on external agents such as wind, water, or animals to move pollen between their reproductive structures. While wind is responsible for pollination of staples such as grains, in many Ontario crops insects form the cornerstone of the pollination service in the agricultural landscape. Bees are the most commonly discussed animal pollinators, although many other insects and even vertebrates are known to pollinate various wild and cultivated plants (see Section 2.0).

Even plants that are considered self-fertile can often realize a benefit in quantity or quality of production from cross-pollination, or even from the activity of insects moving pollen around on the flower that results in more grains being delivered. Even in self-compatible plants, self-pollination is often an "emergency mechanism" used by the plant to assure some reproduction if cross-pollination fails. Seeds and fruits that develop as a result of self-pollination are often smaller and of lower quality than those resulting from cross-pollination, because the plant will preferentially invest resources in cross-pollinated offspring, and others may even be aborted and reduce yield. This document summarizes the current state of knowledge of the pollination biology of Ontario crops, recommends Best Management Practices for pollination of those crops under Ontario conditions, and identifies areas that would benefit from further investment in research.

Pollen and nectar are the resources most sought after by flower-visiting insects, and nectar is typically produced by flowers for the specific purpose of attracting pollinators. Nectar is mostly a sugary liquid (and attractiveness varies directly with sugar concentration), but may also contain other valuable compounds such as lipids, amino acids, vitamins, and minerals. Pollen is high in protein, carbohydrate, lipids, and vitamins, and is valuable to some adult insects as a food source, and particularly to bees as a food for their larvae. When optimizing pollination services, the best results now and in the future will be attained if the needs of both crop and pollinator are as fully met as possible, both when the crop is in bloom, and when it is not. It is important to appreciate that pollination is an ecological interaction, and while beneficial to both participants (*mutualism*), neither participant is performing an altruistic act. The plant will do the best it can to manipulate the visitor into serving as a pollinator, and the visitor will attempt to extract the maximum resources with the minimum of effort, regardless of the resulting reproductive success of the plant. The nectaries are typically positioned in such a way that visitors will have to contact the anthers and/or the stigma (depending on the gender and compatibility of the flower) in order to access the nectar.

In terms of benefit to humans, this fertilization by pollination is critical to the production of viable seed, which in turn is necessary for the growth and development of fruit. Fertilization can only occur if pollen from a source appropriate to the breeding system of the plant is delivered to a receptive stigma, successfully germinates, the germplasm passes through a pollen tube that grows through the style and fuses with the genetic material in an ovule. Thus fertilized, the ovule will begin to produce endosperm, the embryo will develop, and the outer layer will harden into a protective seed coat. If the process is blocked or fails at any one of these stages, no fertilization occurs, the ovule will not produce a viable seed, and the developing fruit may be stunted, malformed, or aborted.

Whether pollinated by wind, animals, or a combination of the two, some (or many) available ovules will likely not be fertilized, a phenomenon referred to as pollen limitation. This term refers to the fact that theoretically all viable ovules could be fertilized and develop into seed, but not enough suitable pollen is delivered to female reproductive structures. Pollen limitation must not be confused with loss of potential or developing seed to other causes, such as disease, drought, or poor soil fertility. In agriculture, unfertilized ovules lead to both quantitative (lower overall yields) and qualitative (small or misshapen fruit that is less valuable than it could be) effects on the produce. Qualitative differences can also be seen in crops not marketed as whole produce, such as oil yield and quality in oilseed crops. Most plants produce many more ovules than can be developed to maturity given the plant's resources, so may abort naturally or be thinned by the farmer, as is common in apple production, for example. However, full pollination of the fruit that does mature will ensure maximal size, symmetry, and market value.

Without the process of pollination in agriculture, production of the fruits and seeds that form the bulk of our produce, and certainly much of its variety, would not be possible. Fertilization of the female flowers are required to produce seeds, and physiological reactions caused by the presence of viable seeds are generally necessary to induce the formation of fruit. The plant may not invest energy and nutrients in seeds and fruit that are inviable or of poor quality, and more seeds generally lead to larger and more attractive fruit. Furthermore, if pollination is poor or incomplete, the resulting fruit may drop, or be malformed, small, asymmetrical, or otherwise of poor quality. All of these factors have the potential to reduce crop yield, quality, or both.

1.2 Basic Flower Anatomy & Function

The systems used by different plant species to reproduce are incredibly varied, and except in cases of *agamospermy*, in which ovules produce viable seed without being fertilized, all involve transmission of pollen to the stigma. Flowers may be male or female, or *hermaphrodite* (both male and female reproductive structures). Single-sex flowers are sometimes called *imperfect flowers*, and hermaphrodite flowers are *perfect flowers*. The terms describing the sexual characteristics of individual flowers should not be confused with that describing the entire plant. A particular plant species may have either individuals that are either male or female (*dioecious*, from the Greek for 'two houses', in that the male and female functions are found in separate plants), or hermaphrodite (*monoecious*, 'one house'). In those species that are monoecious, individual plants may have their male and female functions in separate (imperfect) flowers, in perfect flowers, or they may have two or even all three of the flower types. Monoecious plants may also have sexual functions separated in time, such that the plant or individual flowers on that plant produce pollen at different times than receptive to pollen.

While it could be argued that there is no such thing as a "typical" flower, the incredible variety of floral forms that we see, even within our Ontario crop plants, are derived from the same basic structure. The structure of the flower is designed to facilitate pollination, by whatever system has developed in the particular plant species or variety. This document is primarily concerned with those plants that use insects to transfer their pollen from place to place, although the physics of pollen release and transport on the wind, and subsequent capture by the female floral structures, is no less complex and worthy of study than insect-mediated pollination (see Section 1.3). Flowers that use insect pollinators have developed extremely complex systems of attraction, reward, trickery, and deceit to manipulate the behaviour of the insects to their own ends. For their part, the insects are not interested in assisting the plants to reproduce, but rather in procuring resources, most often pollen and nectar, to feed themselves and their young, and complete their own life cycles.

Inbreeding (self-fertilization or fertilization by close relatives) has negative effects on the fitness of both organisms and populations, possibly reducing the ability to survive and adapt. Within a single generation, individual plants may ultimately be a poor performers and leave fewer offspring, the seeds of which are also known as a crop. While plants do not generally suffer as rapidly or severely as animals do in terms of malformation, loss of function, or even lethal effects, most have mechanisms in place to reduce or eliminate the possibility of fertilizing oneself and producing inbred seed. However, some plants that are considered self-incompatible will also allow self-fertilization as a "back-up" mechanism if cross-pollination does not occur. Flowers that are fully self-compatible, in that they can be fertilized by pollen from the same flower on the same plant (or cross-pollinated), are said to be *autogamous*. Those that are self-compatible but must be fertilized by a <u>different</u> flower on the same plant (or cross-pollinated) are called *geitonogamous*. Those which <u>must</u> be cross-pollinated, fertilized by a genetically different individual of the same species, are *xenogamous*. The most obvious and effective method of ensuring cross-fertilization is to be dioecious, but dioecious plants have no reproductive recourse in cases of serious limitation of cross-pollen. Many different mechanisms to effect self-incompatibility can be found in the plant kingdom, such as male and female flower parts becoming fertile at different times, physical separation of male and female parts within the flower (*herkogamy*), or chemical prevention of the process at any of the steps, including prevention of self-pollen germination on the stigma, pollen tube growth, or fertilization of the ovule.

1.3 Wind Pollination (Anemophily)

Many of the world's most important crop plants are wind-pollinated, particularly members of the grass family such as wheat, rice, corn, rye, barley, and oats. Many economically important forest trees are also wind-pollinated, conifers such as pines, spruces, and firs, and hardwood trees, including several species that are cultivated for nut production (see Section 3.7.3). Ecologically speaking, these plants have opted not to produce resources to attract pollinating organisms to carry their pollen, such as showy flowers, nectar, and scent, but rather produce larger quantities of light, dry pollen, from small, inconspicuous flowers, that can be carried on the wind. Female structures are adapted to capture the passing pollen from the air, but the majority is wasted. Pollination of anemophilous crops is outside the scope of this document.

1.4 Animal Pollination (Zoophily)

Plants, pollinators, and the nature of their mutually beneficial partnerships occur in endless variety. It is important to remember that successful pollination and reproduction is the only goal of the plant. The goal of the animal partner is acquisition of resources, produced at energetic cost by the flower, leading to its own survival and successful reproduction. The plant uses the flower to advertise the presence of resources, including nectar and pollen, and attract the animal pollinator. The animal partner visits the flower, and in the process of collecting resources for its own reproduction, deliberately or accidentally picks up some pollen on its body. An effective pollinator will, in the course of its subsequent foraging activities on that plant species, deliver some pollen to a receptive female. Such a pollinator must interact with the flower in such a manner that the same part of its body that contacted the male anther of the first flower touches the female stigma of the second flower. It must deliver enough pollen to fertilize the ovules in the flower. It must display a level of flower constancy, ensuring that it visits that plant species regularly enough to deliver the pollen before it is lost. An ineffective pollinator fails on at least one of these tasks. It may not deliver enough pollen, it may not deliver the pollen to the correct part of the female flower, or it may simply collect resources such as nectar without moving or even contacting the pollen.

2.0 Pollinators

2.1 Managed Pollinators for Ontario Crops

2.1.1 Honey bee (*Apis mellifera* L.)

The European honey bee has long been considered the standard for agricultural pollination (Robinson et al. 1989). For many of today's beekeepers, pollination contracts are a major source of income, with marketable honey being a secondary product. Indeed, modern cropping systems that consist of large monocultures of insect-pollinated plants would not be possible without the use of honey bee colonies, which are portable and can bring a large work force to a crop in a relatively short time.

Honey bee biology has been studied more extensively than that of any other insect species, and numerous excellent and detailed texts have been written on the topic (i.e. Crane 1990; Caron 2000; Kevan 2007). Honey bees are unusual among temperate zone pollinators in that the queen lives for multiple seasons, and the entire colony hibernates for the winter (ants also do this). During the winter, a healthy colony is able to keep itself warm by metabolizing honey stored in the previous season. When spring arrives and the first flowers begin to bloom, the bees are available to collect resources and pollinate right away, provided that the weather is suitable (honey bees are not effective foragers at temperatures below about 15C). The colony has high requirements for pollen at this time, as the queen begins actively producing brood prior to the end of hibernation, and if sufficient pollen has not been stored, and is not available in the environment, a supplemental feed (pollen substitute, such as FeedBee or BeePro) may be provided by the beekeeper. This ensures a healthy and abundant workforce for even the earliest-blooming crops. As the season proceeds, the colony has a continual strong need for both pollen and nectar, although as brood production drops the pollen (protein) requirements will decrease, and the nectar (carbohydrate) requirements will increase as the colony builds its honey stores for the next winter. Feeding of sugar syrup as a nectar substitute can encourage foragers to collect pollen instead, since not as much nectar foraging outside the hive is required, which can increase the pollination efficiency of the hives (Manning et al. 2010). Attention should be paid to the proper nutrition of the bees if this strategy is employed, however, as nectar frequently contains essential vitamins and minerals in addition to sugar.

2.1.2 Bumble bees (*Bombus* spp.)

Investigation into the management and domestication of bumble bees for pollination, while not so advanced as that of honey bees, has been occurring for over 100 years (Sladen 1912; Plowright & Jay 1966; Velthuis & van Doorn 2006). Commercial availability of bumble bees (*Bombus impatiens*) is now fully established in Ontario, especially for the pollination of greenhouse crops (Kevan et al. 1991a; Morandin et al. 2001a). Due to wise regulations against importation of bumble bees from outside their native range, other species are not currently available (Velthuis & van Doorn 2006). While bumble bee colonies are not nearly as large as those of honey bees, the bees are strong and robust, and are willing to work under cooler and damper conditions than do honey bees (Paarmann 1977; Bosch et al. 2006). Bumble bees do not produce economically significant quantities of honey because nectar is only stored temporarily, and only newly inseminated queens overwinter, founding new colonies in the following spring. Under wild conditions, the large queen emerges in the spring, finds a suitable nesting site such as a vacant rodent burrow or thick tussock of grass, and perform all the work of raising the first brood of workers by herself. Once this brood is raised, the queen will remain in the nest and focus on egg-laying duties, while the workers take over the tasks of foraging, cell-building, and tending the young. When the colony reaches sufficient size, the next generation of reproductive queens and males will be raised. After this task is complete, the colony social structure will break down, and by the onset of winter only the young hibernating queens will still be alive to begin the process again in the spring. This life cycle has been manipulated by commercial bumble bee providers (see Section 8.0) through indoor rearing and husbandry in order to allow mature colonies to be continuously available to customers throughout the entire greenhouse growing season.

Bumble bees have been successfully utilized, or demonstrated promise, for commercial pollination in several outdoor crops, including early blooming species such as some tree fruits that may bloom in weather not conducive to honey bee foraging, and those requiring "buzz pollination". Buzz pollinated plants are those with poricidal anthers, in which the pollen is contained within the anthers and must be shaken out through holes, similar to a salt shaker. In order for this to occur, the visiting bee grabs the base of the anthers in its jaws, disengages its flight muscles from its wings (a feat that cannot be performed by honey bees), and then rapidly vibrates those muscles, making a sharp buzzing sound and vigourously shaking the flower. Crops requiring this type of pollination include blueberry and tomato. Bumble bees have reached their greatest commercial success in greenhouse tomatoes and sweet peppers (Kevan et al. 1991a; Morandin et al. 2001a), where their willingness to function in the still and humid indoor air makes them much more suited to the task than honey bees.

2.1.3 Blue orchard bee (*Osmia lignaria* Fab.)

The blue orchard bee is solitary and does not form colonies of any kind, although its willingness to nest in aggregations has made it suitable to collect and rear at a commercial scale. Currently available bees are the western subspecies *propinqua*, although other species of *Osmia* do show potential for development as managed pollinators (i.e. *O. aglaia*), or are already well established as managed pollinators in other parts of the world (i.e. *O. cornifrons* in east Asia). This bee is active in the spring and early summer, and is an effective forager under inclement weather conditions. As such, it makes an excellent pollinator of tree fruit, and only a few hundred female orchard bees can successfully pollinate an acre of orchard, as has been demonstrated in the U.S. on cherry (Free 1993; Bosch & Kemp 1999; Bosch et al. 2006), and on apple in the Annapolis Valley of Nova Scotia (Sheffield et al. 2008a). The blue orchard bee has been considered as a pollinator of other early-blooming crops, although because it prefers foraging in trees its potential for other Ontario crops may be limited. Management of blue orchard bees for pollination is outlined in detail in Bosch & Kemp (2001) and Mader et al. (2010).

The blue orchard bee is a member of the leafcutter bee family, most species of which build individual cells out of carefully cut leaf pieces in which to lay its eggs. Members of the genus *Osmia* use mud, sometimes mixed with chewed leaves or other materials, to build their cells, and are thus broadly referred to as mason bees. Leafcutter bees construct cells and oviposit within cavities, such as holes in wood or hollow twigs (depending on species), and thus are amenable to culture within nest boxes or aggregations of reed sections or cardboard tubes placed within their habitat. The female orchard bee, having mated, will begin her maternal activities by collecting mud and lining such a cavity at its deepest end. She will then collect pollen and nectar and make a provision ball, on which she will lay an egg when complete. She will repeat this process, building up a line of cells in the cavity until it is full, at which time she will build an "empty cell" and seal off the end of the cavity with a final layer of mud. This empty cell serves as a physical barrier between the developing larvae and parasites that may be seeking to lay eggs on them. Upon completing this series of cells, the female will search for another suitable site, and repeat the process several times until the end of her life.

Those wishing to use mason bees for pollination of tree fruit may purchase the bees as pupae from a commercial supplier, encourage their own population of resident bees in the orchard, or both. Suitable nesting cavities within the orchard are likely to be the limiting factor to the establishment of the bees, so provision of domiciles (i.e. bundles of paper straws, reed or bamboo sections, drilling wooden blocks) is required, whether these boxes remain in place or will be taken into a protected area during the winter. Providing a bucket or dish of mud near the domiciles will be helpful to the bees, which will otherwise need to spend time finding it further afield. Note that nest boxes and other domiciles placed for the benefit of nesting bees may attract woodpeckers and other birds capable of extracting the larvae. Screening the boxes may be necessary to protect the larvae, although this will also render the domiciles less attractive to female bees searching for nest cavities. Finally, it is very important to note that although the bees are present only in the spring and early summer, the activity period is considerably longer than that of the orchard bloom, and thus the bees will require resources for several weeks after their work on the fruit crop is complete if they are expected to produce a generation the following year. Many so-called "weeds" are quality pollen and nectar sources for bees when the crop itself is not in bloom. Planting quality forage flowers that bloom at an appropriate time is also helpful, and may act to suppress competing blooms (i.e. Sheffield et al. 2008b).

Availability and price of blue orchard bees varies considerably between years. See Section 8.0 for links to Canadian providers, and those that will ship to Canada.

2.1.4 Alfalfa leafcutter bee (*Megachile rotundata* Say)

Like the blue orchard bee, the alfalfa leafcutter bee is a solitary member of family Megachilidae. However, unlike the blue orchard bee it is not native to North America. It was developed as a managed pollinator following the decrease in alfalfa seed production observed in the 1940s and 1950s (Pitts-Singer & Cane 2011). Small fields of alfalfa, with a high quantity of edge habitat relative to their area, generally had sufficient service from wild pollinators, particularly bumble bees and larger solitary bees that were physically capable of tripping the alfalfa flowers. However, as alfalfa seed prices climbed and the continuous acreage of fields climbed with them, it was noted that yields declined away from the edges of larger fields, until practically no seed was produced more than 75-100m from natural habitat. Honey bees are generally reluctant pollinators of alfalfa, due to their apparent aversion to being struck forcefully under the head with the stamens when the flower is tripped. Honey bees are capable of effecting pollination, but usually learn to access the alfalfa nectar without tripping the flower, and therefore avoiding moving pollen (see Section 3.4.1). The practice of placing leafcutter bee domiciles in the fields, eventually reaching the dimensions of truck trailers, solved the problem and was the first, and to this date most successful, use of a cavity nesting solitary bee for managed pollination in North America. Experimental investigation of their efficacy of pollination of crops other than alfalfa, notably orchard fruit and berry crops, is also underway.

Problems have emerged in the industry that were largely a result of the artificially high density under which the bees worked, reproduced, and were stored (Bosch & Kemp 2005; Pitts-Singer & Cane 2011). Chalkbrood, a fungal infection similar to the disease of the same name that affects honey bees, is highly virulent to alfalfa leafcutter bees. Furthermore, several species of parasitic wasps (i.e. *Monodontomerus obscurus, Pteromalus venustus*) develop in the cocoons of the bees, killing them. The development of methods to control these insects is difficult, and generally requires the use of insecticides such as dichlorvos (Vapona®), carefully timed so as to kill the target insect, but to not harm the diapausing bees, which are also susceptible.

Husbandry of alfalfa leafcutter bees is sufficiently well understood that cocoons can be manipulated, through temperature management, to emerge at the appropriate time for the bloom of the crop and the local climate (Pitts-Singer & Cane 2011). The cocoon, containing the pupae, must undergo a period of cold after they are fully developed, before they are ready to emerge. The temperature is then warmed to about 30C 2-3 weeks before the bees' services are required. Cocoons are placed into domiciles and placed in the field. Females will return to their place of emergence to lay their eggs, and the next generation of cocoons can be recovered and stored for use next season. Nest blocks that are full should be removed from the field and stored, largely to protect them from insectivorous birds that can be a particular problem at leafcutter domiciles.

2.1.5 Other Managed Pollinators

The development of other wild pollinators into managed pollinators requires considerable investigation into biology, ecology, and husbandry of the species. There are several examples of pollinators being developed to service certain specialized crops, including several species of bumble bees and mason bees are the most likely "new" pollinators to be developed commercially. Efforts to develop native pollinators for management have expanded as concerns have grown about pathogen movement and invasive species resulting from introduced agricultural pollinators. Blow flies (family Calliphoridae), including the familiar bluebottle and greenbottle flies, are suitable pollinators for some vegetable seed production operations and small-scale breeding and experimental work requiring pollination, such as cross-breeding and seed production in carrot. The flies will effectively work in the small screened chambers used for such work, where insects such as bees would not. There is great potential in the biodiversity present on our landscapes, and opportunity to domesticate wild species for particular uses in agriculture. Drone flies, which are members of the genus *Eristalis* of flower flies (Syrphidae) that mimic bees, have also shown some potential for pollination at a commercial scale, particularly in orchards and greenhouses (Free 1993; Jarlan et al. 1997a,b).

2.2 Wild Pollinators

Wild pollinators are usually present anywhere there are insect-pollinated flowers, and often at high abundance and diversity. The services of wild pollinators are free, and their numbers can be encouraged with low-cost measures that improve their nesting habitat and off-bloom food resources. In the United States, the annual value of wild pollinator services has been estimated at three billion dollars (Losey & Vaughan 2006). The proliferation of monoculture cropping across the landscape, coupled with other modifications such as weed control programs can cause considerable harm to their populations. Reductions in wild pollinator populations impacts both their capacity to pollinate wild plants on which our ecosystems depend and their potential to assist with crop pollination (Mineau & McLaughlin 1996; Klein et al. 2007; Spivak et al. 2011). A growing number of producers, with organic operations leading the way, are choosing to encourage wild pollinators on their land.

The benefits of wild pollinator conservation are twofold. First, the grower gains the services of a diverse array of pollinators on the crop, at no financial cost. Research on crops such as canola and watermelon (Kremen et al. 2004; Morandin & Winston 2006) has demonstrated that setting aside a portion of each hectare of land for pollinator habitat and off-bloom resources can increase the net profitability of that hectare. Second, populations of plants in wilderness ecosystems, which rejuvenate our air, water, and energy through their services, will have their pollination services maintained. There is a growing body of evidence that the presence of a diverse floral community can enhance the pollination of crops in some cases, both by attracting pollinators and improving the health of their population through a diverse bloom that is prolonged outside that of the crop. This is in contrast to the traditional view that any and all blooms that may compete with a crop will detract from pollination (Kremen et al. 2002; Morandin et al. 2007; Winfree et al. 2008; Cussans et al. 2010), although this does occur in agricultural areas where pollination service is already compromised (i.e. Ellis & Delaplane 2009).

The presence of competing flowers can be a distraction to bees when they are required on the crop in bloom, particularly when they are more attractive than that crop. While they provide important off-bloom resources to both managed and wild pollinators, blossoms can attract bees to at risk areas such as the vicinity of a field or orchard where a crop is being spraying with pesticides (i.e. white clover; MacRae et al. 2005). A common practice for a crop that is not being adequately pollinated due to low floral attractiveness of the crop, competing blooms, or natural aversion of the honey bees to the flowers (for example, alfalfa) is the addition of more honey bee hives. This can lead to widespread starvation among the managed hives however by exceeding the capacity of that crop to nourish the bees. These situations may be avoided or mitigated if wild pollinators, many of which are more efficient for particular crops (i.e. orchard fruit, alfalfa, vine crops) are encouraged and used instead. Several of the most important groups of wild pollinators are broadly described below, and many of their roles in agricultural pollination are only beginning to be understood.

2.2.1 Bees & Wasps

Ontario is home to approximately 400 species of wild bees as well as numerous species of wasps that visit flowers (some of the latter are also highly effective predators of insect pests). These groups of insects, together with the ants and multitudinous species of minute parasitoids, constitute the order Hymenoptera. Bees are often considered the most important group of pollinators, largely because they actively collect pollen and nectar to provision their young and thus visit many more flowers than those organisms only foraging for their own nutritional needs. Many wasps, although closely related to bees, search for prey or hosts (for parasitic young) and feed on nectar at flowers for their personal energetic needs. Encouragement of wild bee populations requires both off-bloom food resources and the availability of habitat. Many of Ontario's wild bees are ground-nesting species, requiring dry sandy soil with decent structure and low vegetation density; these nests are easily destroyed by deep tillage. Other bees nest in cavities, hollowed twigs and stems, or similar protected spaces.

2.2.2 Flies

There is an incredible variety of flies (order Diptera) that visit flowers. Some of these, such as members of families Syrphidae and Bombyliidae, are adapted to obtain most or all of their resources as adults from flowers. Members of these families can range from somewhat to very hairy, and can move significant quantities of pollen around as they forage. The Syrphidae are probably the most important pollinating flies in Ontario, and under the right conditions numerous species can be very abundant. The larvae of syrphids have a very different ecology, and some can provide additional benefit to crops as the larvae prey on slow-moving insects such as aphids. Most syrphid flies visit flowers to collect nectar only, although some also feed on pollen as adults.

Other flies that can be effective pollinators, including the house flies, blow flies, and anthomyiid flies, also use flowers extensively as adults for their own energetic needs. Some flowers serve as habitat to developing fly larvae as the plant seeds develop, a strategy to which the plant should not object if the ovipositing adult fly also effects pollination. However, this is a reproductive strategy not known to be used by any crop plants grown in Ontario.

2.2.3 Butterflies and Moths

Butterflies and moths (order Lepidoptera) are a large and successful group of insects with plant-feeding larvae (caterpillars) and flying adults with scaled-wings. While some do not feed at all in the adult stage, those that do are restricted to a liquid diet of sugary nectar by their long, straw-like mouthparts, the proboscis. Many use this proboscis to probe for nectar and do not interact strongly with the flower; thus, they often do not get large quantities of pollen on their proboscis or body. However, some plants are specialized to make use of these insects as pollinators, particularly in the tropics.

2.2.4 Beetles

No Ontario crop relies on beetle (order Coleoptera) pollination, although some major crops in other parts of the world are reliant on them, such as oil palm. Beetles tend to visit flowers to feed generally on floral tissue, and may damage the flowers and developing fruit in the process. Some groups of beetles, such as the flower scarabs and members of families Melyridae and Mordellidae are adapted to use floral resources. Some soldier beetles (family Cantharidae) feed extensively on pollen and can move to many different flowers during their adult lives.

2.2.5 Vertebrates

In various tropical areas of the world, vertebrates play an important role in the pollination of many plant species. The most notable are birds and bats, although pollination by other groups such as primates, lizards, and rodents has been recorded. In Ontario few plants have vertebrate pollinators of any significance.

3.0 Best Pollination Practices for Ontario Crops

Cultivated plants have a wide variety of breeding systems, and achieve pollination in different ways. Many important staples, particularly grains such as wheat, oats, rye, corn, and rice, achieve pollination via the wind. Their pollen is produced in very large quantities, reflecting the very small chance of an individual grain landing randomly on a receptive stigma, and individual grains are light, small, and dry, making them easily transported on the air but difficult for insects to handle. They also tend to be nutritionally poor, with starch rather than lipid forming the bulk of energy storage. However, some wind-pollinated crops can be attractive to insect pollinators because the quantity of pollen produced is so large. This attraction can be strengthened if dry conditions or intensive weed control has reduced the availability of other sources of nutrition.

Most fruits, vegetables, forages, and oilseeds require that pollen transfer be carried out by insects, or insects facilitate cross-pollination that improves yield. In modern agriculture, these insects are most often honey bees, although conservation of wild pollinators and evaluation of alternative managed pollinators are strongly encouraged throughout this document. Many crops (i.e. carrot, onion, ginseng) have an associated seed industry, whether for farm producers or garden and nursery retailers, so even if a the fruit or seed is not the marketable, edible part of the plant, knowledge of pollination for breeding purposes and production of viable seed is desirable. Readers interested in details of pollination biology of such vegetable crops not covered by this document are referred to Free (1993), "Insect Pollination of Crops".

Unfertilized ovules may lead to both quantitative (lower overall yields) and qualitative (small or misshapen fruit that is less valuable than it could be) effects on the produce. Developing seeds stimulate the production of fruit tissue, with more viable seeds leading to more tissue, and an even distribution of seeds within the fruit encouraging symmetrical growth. Most plants produce many more ovules than can be developed to maturity given the available resources (sunlight, water, nutrients), and so may abort naturally or be chemically aborted by the farmer, as is common in orchard fruit production, for example. However, full pollination of the fruit that does mature will ensure maximal size, symmetry, and market value. Poor or uneven pollination may also cause economic loss, as the developing seeds or fruit may be aborted later in the growing season if the plant comes under stress.

Many crops that are considered self-fertile may indeed be capable of having their own pollen fertilize their ovules, but for most plants this is undesirable. Thus, plants may have mechanisms other than pollen incompatibility in place to reduce self-fertilization, or they may selectively abort fruit or seeds that result from self-pollination, so as not to use resources in developing inferior (inbred) seed to maturity. Insects can both encourage cross-pollination and facilitate self-pollination via their foraging activities, and therefore can improve yield and productivity of a self-fertile crop.

Note that recommended pollinator rates, for example honey bee hives per hectare, is an estimate of bee requirements based on number of flowers per hectare, the time it takes for a bee to effectively pollinate one (i.e. collect resources), number of bees in a hive that are actively foraging and number of hours per day that they forage, attractiveness of the target blossoms with respect to other crops or weeds that may be nearby, as less attractive crops require more bees to get the required density of pollinators. Any of these factors can vary considerably across an area as large as Ontario, and weather can also strongly affect pollinator activity on a crop. The presence of competing flowers can be a distraction to bees when they are required on the blooming crop, particularly when they are more attractive than that crop, although in some cases removal of competing plants is not as negative as previously though. For example, OMAFRA no longer recommends frequent mowing of competing dandelions in tree fruit orchards, as research has shown that tree fruit pollen is more attractive. Even if some bees forage on the dandelion, the pollination of the tree fruit will not be harmed to a point that economically justifies dandelion control. On the other hand, competing flowers provide important off-bloom resources to both managed and wild pollinators, but can attract bees to the vicinity of a field or orchard, and unfortunately put them at risk when a crop is being spraying with pesticides (i.e. white clover; MacRae et al. 2005).

3.1 Field Fruits & Vegetables

3.1.1 Field & Pickling Cucumbers (*Cucumis sativus*)

Mating & Breeding System: Most cucumber varieties have separate male and female flowers located on the same plant. Most varieties are self-compatible, but due to the physical separation of the floral sexes, insects are required for pollen movement. There are typically more male flowers, which provide pollen, than female flowers on a given plant, and the male flowers mature first on an individual plant. Both male and female flowers produce nectar, and the male nectar has a higher sugar concentration than the female (Delaplane & Mayer 2000). Typically, pollen is collected by bees in the morning, and foragers will switch to nectar in the afternoon, working both genders and delivering the large, sticky pollen grains in the process (Delaplane & Mayer 2000). Fertility of the plant, however, is greatest in the morning and declines as the day progresses. Flowers of both sexes are typically open for only a single day, following which male and insufficiently pollinated female flowers will drop. Some male-sterile hybrid varieties have been developed with only female flowers, intended to increase the yield, but which require interplanting of male-fertile varieties to provide pollen (Bodnar 1987; Free 1993). Ovaries vary in length and number of ovules, with more ovules translating to larger fruits. Larger, older vines tend to produce larger flowers. Maturing fertilized fruit will inhibit development of new female flowers, and therefore limit the number of fruits an individual vine can produce.

Pollination, Quality & Yield: The material presented here applies only to field and pickling cucumber pollination, since varieties grown in Ontario for fresh consumption are parthenocarpic, meaning that they develop without fertilization of the ovules. Pollination of these varieties is undesirable as it leads to fruits of diminished marketability due to their irregular and uneven shape. Pollination may be reduced in these crops by growing them in greenhouses, planting more attractive crops near outdoor fields, removal of male flowers, and restricting the use of honey bees in the vicinity during the bloom time of the cucumber.

For pickling cucumbers, improved pollination can increase the number of seeds in individual fruits, and also increase yield per hectare over unpollinated crops or those pollinated by hand (Canadian Dept. of Agriculture 1961; Kauffeld & Williams 1972; Gingras et al. 1999; Nerson 2009). Pollination of these varieties also improves the shape and value of the individual fruits, in contrast with the parthenocarpic varieties discussed above. Cucumbers, like other cucurbits, have numerous ovules and thus require a great deal of pollen for full pollination. As many as 18 visits by pollen carriers to female flowers are necessary for full pollination (Kauffeld & Williams 1972; Lord 1985; Stanghellini et al. 1997; Gingras et al. 1999; Nerson 2009). Flowers with larger ovaries tend to be produced by older vines, so there is value in delaying pollination in order to produce larger fruits with more seeds (monoecious varieties), or planting male plants several days after female plants in gynoecious varieties to ensure pollen availability at the correct time (Delaplane & Mayer 2000).

Pollination Recommendations: Honey bees are highly effective pollinators of cucumber, able to provide the required visits and pollen delivery (Connor & Martin 1969; Connor et al. 1975). Depending on planting density, 2.5-8 hives per hectare are recommended (Kevan 1988; Free 1993; Scott-Dupree et al. 1995) to sufficiently pollinate available female flowers in order that they produce well-formed fruit. Planting density in the crop varies considerably, and these stocking recommendations are also expressed as one honey bee colony per 50000 plants (Kevan 1988). The bees should be placed in shaded areas at the edge of small fields, and can be placed in the crop itself in larger fields to provide sufficient pollination, in such an arrangement that any point in the field is no more than 250m from a hive. However, in the latter case shade and water should be provided for the bees on hot days (Bodnar 1987). Bumble bees can be more effective pollinators than honey bees due to their earlier foraging hours and higher floral visitation rate (Stanghellini et al. 2002), but may find greatest practical utility on pickling cucumbers in greenhouses due to the large number of expensive colonies that would be required in a field situation. If a male-sterile variety is used, care must be taken to plant a pollenizer variety in the field, at a rate of 5-15% of total seed (Bodnar 1987). In this plan, honey bees (which naturally prefer staminate flowers, even though their prime target is nectar) are forced to more frequently visit the female flowers, delivering pollen and increasing the number of fruits produced. The use of brood pheromone has been demonstrated to improve pollen foraging by honey bees on cucurbits in the southern U.S. (Pankiw 2004), and its potential for use in Ontario should be further investigated.

Small and large ground-nesting bees are effective cucumber pollinators, but are rarely present at sufficient densities to perform the service at an agricultural scale. In small fields of cucurbits, or in large fields managed with them in mind, the native squash bee *Peponapis pruinosa* does an admirable job of cucurbit pollination (Willis & Kevan 1995; Julier & Roulston 2009). This ground-nesting bee works in the early morning, when the flowers are at their highest fertility (Tepedino 1981; Willis & Kevan 1995; Sampson et al. 2007; Julier & Roulston 2009), and can reach very high densities at the field margins and within the field itself. Other wild bees, particularly bumble bees, are also effective cucurbit pollinators (Delaplane & Mayer 2000).

3.1.2 Melons (muskmelon incl. honeydew, canteloupe, sweetmelon) (*Cucumis melo*)

Mating & Breeding System: This species contains several commonly cultivated varieties that are both self-fertile and inter-fertile, meaning that the plants can be fertilized by either their own pollen or that of another individual, and also that pollen from different varieties are capable of successfully fertilizing one another. However, in many varieties the male flowers on an individual plant are not mature at the same time as hermaphrodite or female flowers. Insects, including honey bees, are required to move pollen from flower to flower (Mann 1953). In most varieties, male and female structures are both present on each individual plant, although there is variability in how they are distributed amongst the flowers (Free 1993). For example, some varieties may have separate male and female flowers, others may have male and female parts in the same flowers (hermaphrodite, or 'perfect' flowers), while still others may have hermaphrodite flowers together with separate male or female flowers on the same vine. There are typically more male flowers, which provide pollen, than female flowers, and the male flowers mature first on an individual plant. Both male and female flowers produce nectar, and the male nectar has a higher sugar concentration than the female (Delaplane & Mayer 2000). Typically, pollen is collected by bees in the morning, and foragers will switch to nectar in the afternoon, working both genders and delivering the large, sticky pollen grains in the process (Delaplane & Mayer 2000). Fertility of the plant, however, is greatest in the morning and declines as the day progresses. Flowers of both sexes are typically open for only a single day, following which male and insufficiently pollinated female flowers will drop.

Pollination, Quality & Yield: Melons and other cucurbit species (watermelon, pumpkin, squashes, etc) are generally capable of producing hundreds of seeds per fruit, and require successful delivery of a suitable amount of pollen to effect this massive fertilization. Varieties of *Cucumis melo* typically require a minimum of 400 fertilized ovules per melon to produce a marketable fruit, and could have up to 600 or more fertilized ovules. Insect pollination is essential for these crops, increasing yield per hectare and improving the size, quality, and marketability of the fruit. Improved pollination of melon can increase the number of seeds of individual fruits and overall yield of the crop (Nerson 2009).

Pollination Recommendations: It is recommended to provide 2.5 strong colonies of honey bees hectare in large fields (Bodnar 1987; Kevan 1988). In small fields of cucurbits, or in large fields managed with them in mind, the native squash bee *Peponapis pruinosa* does an admirable job of pollination (Willis & Kevan 1995; Julier & Roulston 2009). This ground-nesting bee works in the early morning, when the pollen has its highest fertility (Tepedino 1981; Willis & Kevan 1995; Sampson et al. 2007; Julier & Roulston 2009), and can reach very high densities at the field margins and within the field itself. This bee, together with other effective wild bees, nests in the ground in and around the crop, so care must be taken to avoid damage to its nests that may be caused by deep tillage (Willis & Kevan 1995; Delaplane & Mayer 2000; Shuler et al. 2005). Male squash bees are also active pollinators, as they feed on nectar and seek females inside blossoms (Cane et al. 2011).

3.1.3 Watermelon (*Citrullus lanatus*)

Mating & Breeding System: Most watermelon varieties bear both male and female flowers, although a few have male and hermaphrodite flowers. Individual plants are self-fertile, but require the action of a pollinator to effect pollination, even within a hermaphrodite flower. Seedless watermelon varieties, which are triploid and produce inviable pollen, must generally be interplanted with a diploid pollenizer variety, since successful fruit set will require viable pollen from the pollenizer (Walters 2005; Dittmar et al. 2009, 2010).

Pollination, Quality & Yield: There is a strong correlation between the weight of a mature watermelon and both the number and weight of mature seeds present in the fruit. Seedless watermelon require an even greater number of pollinator visits to set marketable fruit, because pollen must be carried from a pollenizer variety further away (Stanghellini et al. 2002; Walters 2005). Experiments have shown a positive effect of adding honey bees on melon weight and/or number of melons per plot (Brewer 1974; Spangler & Moffett 1979; Rao & Suryanarayana 1988). Stanghellini et al. (1998) found that bumble bee visits produced significantly greater seed set per visit than did honey bees. It is also likely that local wild pollinators are capable of effecting pollination in commercial watermelon fields, but if these are lacking then addition of managed pollinators (honey bees or bumble bees) will be required for successful fruit set. It has been observed that yield is better near the margins of large fields than in the centre, implying the activity of wild pollinators nesting in these habitats (Goff 1937). Growers could improve pollination and reduce their costs by managing their fields and surrounding habitat to encourage wild pollinators in and around their fields (i.e. reduced mowing, judicious use of pesticides, conserving marginal areas and hedgerows), in addition to managed pollinator use. This will allow them to best understand the pollinator availability in their individual fields, and develop wild pollinator populations on the farm.

Pollination Recommendations: Honey bees remain the pollinator of choice for watermelon, readily providing the large numbers of visits required to set high quality fruit, even in seedless (triploid) watermelon crops (Walters 2005). In larger fields at least, addition of honey bees should be added to improve pollination at a rate of 1-2.5 strong colonies per hectare (Kevan 1988). Shade and water should be provided for the bees on hot days (Bodnar 1987). Managed bumble bees have also been shown to be highly effective pollinators of watermelon, and capable of delivering the large quantity of pollen required for marketable watermelon via their early foraging hours and high floral visitation rate (Stanghellini et al. 1998, 2002). Further investigation of bumble bee use in commercial watermelon production is warranted. The hoary squash bee (*Peponapis pruinosa*) is an excellent pollinator of cucurbits (Willis & Kevan 1995; Shuler et al. 2005; Julier & Roulston 2009), although research into its activity and effectiveness, together with that of other wild solitary bees, on watermelon is required.

3.1.4 Squash, Pumpkins, Zucchini & Other Gourds (*Cucurbita* spp.)

The genus *Cucurbita* contains several species, with multiple varieties within each, that are familiar vegetables cultivated in Ontario. The group includes varieties of pumpkins, numerous varieties of edible winter and summer squash, edible and ornamental gourds, and zucchini (sometimes known as courgettes). Many people do not realize how closely related these seemingly diverse products are.

Mating & Breeding System: Individual plants bear separate male and female flowers, with many more male flowers usually being present. Most varieties are self-compatible, but due to the physical separation of the floral sexes, insects are required for pollen movement. Pollen is released in the morning, and fertilization and fruit development is most successful if pollinators are active at this time. Female flowers have a three-part ovary, and the numerous ovules within require large quantities of pollen for sufficient fertilization to produce a marketable fruit. Pollen grains must be moved between flowers by an insect pollinator. The plants are self-fertile, but since each female flower requires numerous pollinator visits to complete fertilization, each fruit likely represents a mixture of self- and cross-pollinated seeds. Both male and female flowers produce nectar, and the male nectar has a higher sugar concentration than the female (Nepi & Pacini 1993; Delaplane & Mayer 2000). Typically, pollen is collected by honey bees in the morning, and foragers will switch to nectar in the afternoon, working both genders and delivering the large, sticky pollen grains in the process (Delaplane & Mayer 2000). Fertility of the plant, however, is greatest in the morning and declines as the day progresses. Flowers of both sexes are typically open for only a single day, following which male and insufficiently pollinated female flowers will drop.

Pollination, Quality & Yield: Large quantities of pollen must be delivered to a female flower if it is to set a marketable fruit. Native bees such as bumble bees and the hoary squash bee (*Peponapis pruinosa*), a specialist pollinator of these crops that is found frequently in Ontario where cucurbits have been continuously grown for a suitable length of time (Willis & Kevan 1995; Shuler et al. 2005; Julier & Roulston 2009), will begin foraging considerably earlier than honey bees. Cross-pollination also delivers larger individual fruits. Nerson (2009) did not find a relationship between the quantity of pollen delivered to the female flowers and yield or number of fertilized seeds per fruit. However, Walters & Taylor (2006) found that while wild pollinators were typically sufficient for fruit set in pumpkin, addition of honey bees were required to maximize the number of visits per flower, and therefore size and value of the resulting fruit. They also reported more fruit, heavier fruit, and more and larger seeds in the presence of honey bees. It should be noted, however, that there was significant pesticide use in the plots during the trials, which may have compromised the activity of the wild bees.

Pollination Recommendations: Different varieties within the same species of *Cucurbita* will cross-pollinate if blooming simultaneously. This will likely lead to undesirable characteristics in the resulting product, and therefore varieties should not be grown near each other, especially if seed is desired for future planting. The native hoary squash bee (*Peponapis pruinosa*) is an excellent pollinator of cucurbits, as it concentrates on the crop and is active in the early morning when flowers are at their most fertile (Tepedino 1981; Willis & Kevan 1995; Sampson et al. 2007; Julier & Roulston 2009). This bee nests in the ground in and around the crop, so care must be taken to avoid damage to its nests, particularly during cultivation (Willis & Kevan 1995; Shuler et al. 2005). Male squash bees are also active pollinators, as they feed on nectar and seek females inside blossoms (Cane et al. 2011). Managed honey bees and bumble bees are excellent pollinators, although their presence in a field may be superfluous if adequate wild pollinator populations are present. In larger fields at least, addition of honey bees or bumble bees should be considered to improve pollination in the center of the field. Recommended stocking rates vary widely, however, from 1-8 colonies per hectare (Kevan 1988; Delaplane & Mayer 2000, and references therein) depending on plant density. Shade and water should be provided for the bees on hot days (Bodnar 1987; Artz & Nault 2011). Artz & Nault (2011) found that commercially available bumble bees (*Bombus impatiens*) significantly outperformed both honey bees and the hoary squash bee in small fields. Further research is required to determine suitable densities of hive placement, since the ability of honey bees to pollinate these crops may have been overestimated due to failure to account for activity of wild bees. Wild bee populations, particularly that of the squash bee, can generally be sufficient to pollinate squash and pumpkin on farms managed with appropriate practices (Delaplane & Mayer 2000; Shuler et al. 2005; Julier & Roulston 2009).

3.1.5 Peas (*Pisum sativum*)

Very little cross-pollination occurs in garden pea, as the anthers dehisce prior to the opening of the flower bud, and are self-fertile. Some pollinators will collect pea pollen, and pest infestations (i.e. thrips) can also result in cross-pollination rates as high as 20%. There is some evidence that this can increase yield, but in general the pea flowers are not designed for, nor need, pollination by insects.

3.1.6 Green Beans (*Phaseolus* spp.)

Mating & Breeding System: The genus *Phaseolus* includes several commonly cultivated beans, such as the common green bean, snap bean, pole bean, kidney bean, and haricot (all varieties of *P. vulgaris*), lima bean (*P. lunatus*), and scarlet and runner beans (varieties of *P. coccineus*). While some *Phaseolus* species are capable of self-pollination, many species and varieties have improved yield if insects are allowed access to the flowers, which produce significant quantities of nectar and pollen, and hand pollination experiments suggest that this is at least partially due to increased cross-pollination. In contrast, *P. lunatus* appears to be almost entirely self-pollinated, with pollination occurring inside the flower prior to opening. Although *P. vulgaris* is also self-pollinated prior to opening, cross-pollination does occur due to insect visits because all ovules are not fertilized prior to the flower opening (Free 1993; Ibarra-Perez et al. 1999). Despite this, some varieties of *P. lunatus* and *P. vulgaris* produce large quantities of concentrated nectar that are attractive to pollinators, although the pollen does not seem especially palatable to most. *P. coccineus* is known to require insect pollination, typically by bees, to set a crop (Labuda 2010).

Pollination, Quality & Yield: Yield and seed quality of scarlet bean and runner bean (*P. coccineus*) is increased up to 10-fold by the presence of insect pollinators, particularly large-bodied bumble bees and carpenter bees. Honey bees are capable of working the flowers, but do not seem to actively collect pollen or facilitate cross-pollination as do the other, larger bees. In *P. vulgaris*, there can be a significant benefit to cross-pollination by insects, attributed to improved seed set following tripping of the flowers, which is best effected by bumble bees (Ibarra-Perez et al. 1999). Other species of *Phaseolus* such as *P. lunatus* are largely self-pollinated, and yield or quality are not significantly affected by the addition of pollinators.

Pollination Recommendations: Experiments with caged honey bees have demonstrated that insect-vectored pollination occurs, although superior results are seen in *P. coccineus* if bumble bees have access to the flowers. The small increase seen in *P. vulgaris* and *P. lunatus* when bees are used to supplement cross-pollination is probably not profitable for the grower. However, further research into the best managed pollinators for the task, and the magnitude and mechanism of the improvement, would be valuable, particularly for *P. vulgaris*.

3.1.7 Broad Beans (*Vicia faba*)

Mating & Breeding System: *Vicia faba* includes two cultivated varieties, the broad bean and the field bean, with large and small seeds, respectively. Flowers are hermaphroditic, and both self- and cross-pollination are possible and appear to be facilitated by visiting bees. The flowers are typically leguminous (see Section 1.2), adapted to 'trip' when visited by a pollinator, with the result that pollen is actively dusted on the visitor. This suggests that cross-pollination is advantageous, and indeed many of the pods that reach maturity in a given crop are from cross-pollinated flowers. It has been observed that the plants produce many more flowers than they can mature, and many are aborted either before or after fertilization (Riedel & Wort 1960; Crofton 1996). Self-pollination is undesirable, as the offspring of outcrossing varieties have shown a tendency to become inbred and poor producers (Crofton 1996; Mussalam et al. 2004). This occurs through self-pollination in the absence of adequate insect pollination service, as phenotypic characteristics favouring self-pollination, such as style length, become more pronounced (Kambal et al. 1976; Crofton 1996). There is significant uncertainty surrounding the interaction between hereditary factors and fruit abortion due to environmental conditions (particularly water stress) in this crop (McVetty & Nugent-Rigby 1984; Crofton 1996). With sufficient pollination service, the proportion of outcrossed individuals in a population typically is about 30-35% (McVetty & Nugent-Rigby 1984 and citations therein; Stoddard & Bond 1987).

Pollination, Quality & Yield: A typical crop is composed of a mixture of lower-yielding inbred and higher-yielding hybrid plants, with the latter requiring insect pollination to achieve the higher yield. The presence of insect pollinators has a beneficial effect on total yield, productivity per plant, and size of individual seed, although results vary widely across studies in different parts of the world, including Australia, Africa, and Europe (Free 1966; Free & Williams 1976; Stoddard 1991; Somerville 1999; Al-Ghamdi & Al-Ghamdi 2003; Mussalam et al. 2004; Aouar-Sadli et al. 2008). Honey bees are capable of effecting pollination, although as with many large-flowered legumes, larger and stronger bees seem to do a superior job. It has been demonstrated that inbred plants must be cross-pollinated to set fruit, and that the mechanism that prevents self-pollination appears to be physical (Drayner 1959). Hybrid plants are self-fertile, and appear to act as a safeguard in the event of a poor year for pollinators. However, the following year the progeny of self-fertilized hybrid plants will be inbred, and produce very few seeds without insect pollination. Thus, it is beneficial to ensure adequate insect pollination for both the current crop, and future crops that may be grown from that seed. The presence of bees also appears to allow the plant to set fruit earlier (Hebblethwaite et al. 1984).

Pollination Recommendations: Additional research in several areas of faba bean pollination would be useful in developing the crop in Ontario. It has been suggested that while honey bees are effective pollinators in warmer climates, in temperate zones such as Ontario they may be less effective (McVetty & Nugent-Rigby 1984; Stoddard 1991). Furthermore, it is possible that while adding honey bees is beneficial, use of too many hives may be superfluous, as the plants will only set fruit from a portion of their flowers no matter how many are pollinated, and abort the rest (Stoddard 1991). Scott-Dupree et al. (1995) recommend a stocking rate of 2.5 honey bee colonies per hectare. It has been shown that plants in small fields and those near the edge of large field show improved productivity, demonstrating the value of wild pollinators in this crop (Bond & Pope 1974; Free & Williams 1974; Bond & Kirby 1999). In Canada, bumble bees, miner bees (Andrenidae) and digger bees (Apidae: Anthophorinae) are the most important wild pollinators (Stoddard & Bond 1987). Free & Williams (1976) demonstrated that fields greater than 12 hectares had reduced productivity in the center, and suggested that addition of honey bees on fields greater than this size could be beneficial, but this has not been rigorously investigated. Because honey bees have difficulty reaching nectar in the faba bean, beekeepers may wish to supplement their hives with sugar syrup while they collect pollen on this crop.

3.1.8 Field Tomatoes (*Lycopersicon esculentum*)

Mating & Breeding System: Tomato flowers grow in loose inflorescences, and hang with the reproductive organs oriented downwards. They do not produce nectar, so a pollinator must be willing to only forage for pollen if they are to visit the flowers. The pollen is produced within the anthers, and must be shaken out through small pores (Buchmann 1983; Plowright & Laverty 1987). A visiting bee must collect pollen by hanging upside-down from the flower, grasping the stamens in its mandibles, and "buzzing" to agitate the flower. The pollen will then be shaken out through pores in the anther onto the underside of the foraging bee, where it can be brushed into their pollen baskets using the legs (Buchmann 1983; Plowright & Laverty 1987). The flowers are self-fertile, yet the probability of self-pollination varies with different varieties according to the relative timing of stigma receptivity, pollen availability, and the relative length of stigma and stamens. In the absence of animal pollinators, the wind may provide sufficient agitation leading to self-pollination and fruit set.

Pollination, Quality & Yield: There is a relationship between the quantity of pollen delivered and distribution of its delivery on the stigma, and with the marketability of the fruit in terms of size and shape. Tomatoes can be fully pollinated by self- or cross-pollen, and there is no evidence that cross-pollination improves quality. There is evidence that the quantity of pollen on the stigma is related to the rate of development, size and shape of the fruit, and/or the number of seeds produced (Kevan et al. 1991a; Dogterom et al. 1998; Morandin et al. 2001a).

Pollination Recommendations: The use of bumble bees to pollinate tomatoes in Ontario greenhouses is well established (see Section 3.6.1), but the practice is less advanced for field tomatoes. Tomato pollinators must be able to buzz pollinate the flowers, making bumble bees the ideal choice. Honey bees will forage on tomatoes for pollen, but most members of a colony will seek nectar plants elsewhere. The effectiveness of wild bees in tomato pollination has been demonstrated by at least one study (Greenleaf & Kremen 2006a) Due to their incapability of buzz pollination, when honey bees are placed on field tomatoes it is possible that much of the fruit set is due to the action of wind or of wild insects that can buzz pollinate, such as bumble bees and miner bees (Andrenidae).

3.1.9 Field Sweet and Hot Peppers (*Capsicum annuum*)

Mating & Breeding System: Cultivars of this plant include both sweet peppers and many varieties of hot peppers, all originating from Latin America. This discussion will be limited to sweet bell peppers, as production of hot peppers in Ontario rarely reaches a commercial scale beyond local markets. Much of the material presented, however, applies to hot pepper varieties, and a variety of insects will visit the flowers. It should be noted, however, that many hot pepper growers are hobbyists who prefer controlled cross-breeding, and should therefore take steps to prevent open pollination. Although pepper flowers produce nectar in addition to pollen, they are self-fertile, and most flowers can set fruit without cross-pollination. Like many members of the Solanaceae, peppers require physical agitation to release pollen from porous anthers, which can be accomplished by wind and/or buzz pollination by certain visiting insects (i.e. Raw 2000). The flowers have a large ovary surmounted by a style that is generally longer than the surrounding stamens. The stigma is generally receptive prior to the release of pollen (Free 1993).

Pollination, Quality & Yield: While evidence demonstrates that fruit set and yield is related to the bearing capability of the plant, either through breeding or resource availability, there is some indication that cross-pollination by insects can increase the number of seeds and size of individual fruits (Free 1993). Some of the cross-pollination attributed to insects may actually be the result of wind in field sweet peppers.

Pollination Recommendations: There has been considerable work examining the use of managed pollinators in greenhouses, because the lack of both wind and wild pollinators results in a lack of self- and cross-pollination. However, little research has been conducted into the benefits of using managed pollinators on peppers grown under field conditions. In Brazil, Raw (2000) demonstrated the effects of wild bees on hot pepper pollination, including undesirable crossing of hybrid lines resulting in inferior product. It is entirely possible that insect pollinators could also improve pollination in Ontario, but it is likely that the total economic benefit of adding honey bees or bumble bees to pepper fields would be fairly small, particularly if healthy wild pollinator populations were present.

3.2 Orchard Fruit

3.2.1 Apples (*Malus* x *domestica*)

Mating & Breeding System: The flowers of apple are perfect, with five styles that are associated with a carpel bearing a pair of ovules, and numerous stamens. The styles, however, unite near their base with the result that pollen delivered to one stigma can travel down the style and fertilize an ovule associated with a different stigma. It is thus possible, at least in certain cultivars, for all ovules to be fertilized and the flower fully pollinated even if not every stigma in the flower receives pollen (Sheffield et al. 2005). The flowers of apple are incapable of self-fertilization, even within a cultivar, and require insect cross-pollination with pollen from a different cultivar (a *pollenizer*) in order to set fruit and produce seeds.

Pollination, Quality & Yield: The largest, most symmetrical and most valuable apples are produced when full pollination occurs. Unfertilized flowers will drop, and poorly fertilized fruit are also more likely to be shed within a short period of time. Those fruit that do develop will be malformed and small. It should be noted that although apples often produce many more flowers than can develop into fruit, and growers generally thin flowers to favour development of larger fruit, this is a question of plant resource investment rather than pollination. Pollination of the desired flowers is still required, and insects must carry the pollen from the pollenizer to those blossoms. Early fertilization is also desirable to allow the most time for development of mature fruit. Flowers of some apple cultivars may show ovule degeneration prior to fertilization, which may result in fruit with few seeds that are ultimately shed (Hartman & Howlett 1954).

Pollination Recommendations: As a general rule in tree fruit orchards, planting a pollenizer cultivar as every third or fourth tree in a staggered pattern will ensure that each main cultivar tree is adjacent to a pollenizer (Free 1993; Wilson & Elfving 2000; Kron et al. 2001a,b). Thus, it is necessary to plant pollenizers of a different cultivar in the orchard, in some cases other species of *Malus*, such as crabapple (despite being different species, they are capable of fertilizing ovules and developing into seed). Some ornamental *Malus* have been bred to produce huge numbers of flowers, and carry the added benefit that their resulting fruit are unlikely to be confused with the apple crop (Williams 1977; Mayer et al. 1986; Free 1993; Wilson & Elfving 2000). The ideal pollenizer will have flowers with similar colour and reward to the main cultivar, so that pollinators do not display a preference for one over the other, and thus reduce the potential for cross-pollination (Mayer et al. 1989a). The pollenizers should be staggered throughout the orchard in such a manner that no tree should be further than 20 meters from a pollenizer tree (Wilson & Elfving 2000; Kron et al. 2001a,b). In some modern orchards, a branch of the pollenizer is grafted onto the production trees to provide the pollen. In the latter case, however, care must be taken to ensure that there are enough pollenizer branches, and that they flower in sufficient density, to adequately service the production trees. Pollenizer cultivars vary in effectiveness on different production cultivars, and growers should confirm that their choice of pollenizer is suitable for cross-pollination with the production cultivar when planning an orchard.

Honey bees are traditionally used to pollinate apples and remain the pollinator of choice. The recommendation of 2-5 colonies per hectare is dependent on age of orchard and size of trees (Kevan 1988; Scott-Dupree et al. 1995), with modern orchards of trellised dwarf trees requiring the high end of the range, or even more. The hive or domicile openings should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995; Delaplane & Mayer 2000). Problems with fertilization may arise due to the early flowering period, when the weather is often inclement in the spring. Honey bees will not forage below 15C or if there is too much wind or dampness, and loss of time working the crop can have serious negative effects on fruit set and yield (Benedek & Nyeki 1996). It should be noted, however, that cold temperatures can also hamper the physiological process of pollen tube growth and fertilization, leading to problems with fruit set and seed production. More colonies and/or the use of appropriate pollen dispensers (see Section 4.5) can accelerate pollination and reduce the amount of suitable weather required (Townsend et al. 1958). Species such as bumble bees and blue orchard bees have shown to successfully pollinate apple during inclement weather, and their use should be considered at least as a contingency by growers (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Wild bees and possibly even flies are also valuable (see Section 2.2), particularly in small orchards adjacent to areas such as forest and wetlands that provide nesting habitat (Boyle & Philogene 1983; Sheffield et al. 2008a), although specific management to increase their populations would be required in most situations (Scott-Dupree & Winston 1987; see Section 2.2).

Management of competing blooms in the orchard is an important concern in facilitating pollination, but must be undertaken with care and with the overall pollination strategy of the orchard in mind. If establishment of alternative pollinators such as the blue orchard bee are of interest to the grower, provision of alternative forage is required, in order that the bees have sufficient bloom resources to complete their life cycle and provide adequate nutrition. While both sufficiency of resources and nutrition are concerns for managed pollinators, it is important to avoid competition with the crop for pollination services in order to make most efficient use of those services. This is particularly important when the crop is less attractive to foraging insects than the weeds. Growers should mow (not herbicide) competing blooms during fruit bloom only. However, growers should also be aware that weeds may attract bees to orchards off-bloom, which can result in bee kills for neighbouring beekeepers if insecticides are used on the fruit crop (see Section 5.0).

3.2.2 Pears (*Pyrus communis*)

Mating & Breeding System: The flowers of pear are perfect, with five styles that are each associated with a carpel bearing a pair of ovules, and numerous stamens. The flowers are self-incompatible, and require cross-pollination with pollen from an appropriate pollenizer cultivar and carried by insects in order to set fruit and produce seeds.

Pollination, Quality & Yield: Cross-pollination with a compatible pollenizer cultivar is necessary for fruit set in pear, and insects are required to carry the pollen from the pollenizer to those blossoms (Slingerland et al. 2002a). The largest, most symmetrical, and most valuable pears are produced when full pollination occurs. Unfertilized flowers will drop, and poorly fertilized fruit are also more likely to be shed within a short period of time, and those that do develop from poorly pollinated flowers will be malformed and small (Free 1993). Early fertilization is also desirable to allow the development of mature fruit. Attracting bees to pear flowers can be difficult, as the sugar concentration of the nectar is low (Konarska et al. 2005), although pollen foragers find the flowers appealing. This characteristic may have developed due to the early flowering time and lack of competition for pollinators from other plant species. Also, pears bloom in the spring, and pollination may suffer from low insect activity due to inclement weather.

Pollination Recommendations: Pears are self-incompatible, and a tree cannot be fertilized by its own pollen, or even the pollen of a tree of the same cultivar. Pollenizer cultivars should be approximately 10-15% of the trees in the orchard, spaced evenly such that no production tree is more than two trees from a pollenizer (Slingerland et al. 2002a). Honey bees are traditionally used to pollinate pears and remain the pollinator of choice, but problems and poor fertilization may arise due to the early flowering period, when the weather is often inclement in the spring. The standard recommendation to facilitate pollination in pear is 2-5 strong colonies of honey bees per hectare, to be placed in the orchard when 10-20% of flowers are in bloom (Kevan 1988; Scott-Dupree et al. 1995; Slingerland et al. 2002a). It is important that enough pear blooms be present to attract the bees, so they do not leave the orchard to seek food elsewhere. Honey bees will not forage below 15C or if there is too much wind or dampness, and loss of time working the crop can have serious negative effects on fruit set and yield (Benedek & Nyeki 1996). The hive or domicile openings should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995; Delaplane & Mayer 2000; Slingerland et al. 2002a). Pollinators such as bumble bees and blue orchard bees may be valuable for pear pollination during inclement weather, although research is necessary into their effectiveness for this particular crop (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Jacquemart et al. (2006), working in Europe, found that bumble bees were more likely than honey bees to cross-pollinate pear. Wild bees and possibly flies are may also be valuable (see Section 2.2), particularly in small orchards adjacent to suitable wild habitat, although specific management to increase their populations would be required in most situations (Scott-Dupree & Winston 1987).

Due to the poor sugar content of pear nectar, it is essential to mow competing blooms if any are present in the orchard during the pear bloom period. Do not spray herbicides in the orchard when pollinators are present. Management of competing blooms in the orchard is an important concern in facilitating pollination, but must be undertaken with care and with the overall pollination strategy of the orchard in mind. If establishment of alternative pollinators such as the blue orchard bee are of interest to the grower, provision of alternative forage is required, in order that the bees have sufficient bloom resources to complete their life cycle and provide adequate nutrition. While both sufficiency of resources and nutrition are concerns for managed pollinators, it is important to avoid competition with the crop for pollination services in order to make most efficient use of those services. This is particularly important when the crop is less attractive to foraging insects than the weeds. Growers should mow (not herbicide) competing blooms during fruit bloom only. However, growers should also be aware that blossoms may attract bees to orchards off-bloom, which can result in bee kills if the grower uses insecticides (see Section 5.0).

3.2.3 Plums (several *Prunus* spp.)

Mating & Breeding System: Flowers in genus *Prunus* are similar to those of apple and pear, except that they only possess one style and one ovary containing a pair of ovules. The flowers of most cultivars are incapable of self-fertilization, and require cross-pollination with pollen from an appropriate pollenizer cultivar and carried by insects in order to set fruit and produce seeds (Manino et al. 1995; Calzoni & Speranza 1998; Sapir et al. 2008). The most commonly cultivated species in Ontario are the European plum (*P. domestica*) and Japanese plum (*P. salicina*). In North America, cultivated plum includes at least two additional species (*P. insititia*, *P. americana*) which are less suited to the Ontario climate. Each species contains numerous cultivars (Slingerland & Lay 2007), but being different species, cultivars of European plum will not pollinate Japanese plum and vice-versa. Plums are also sometimes crossed with apricots (Section 3.2.6) to produce "plumcots", which varies widely in yield and fruit set depending on which species supplied the pollen in the cross. Plumcots require an apricot pollinizer for reliable fruit set (Jun & Chung 2007).

Pollination, Quality & Yield: Cross-pollination with a compatible pollenizer cultivar is necessary for fruit set in plum (Manino et al. 1995; Calzoni & Speranza 1998), and insects are required to carry the pollen from the pollenizer to those blossoms. Because each flower contains only one pair of ovules, asymmetry of poorly pollinated fruit is less of a problem than in the pome fruits. If neither is fertilized, the flower will wither and drop, and if both are fertilized then the flower is fully pollinated and a symmetrical fruit is expected, with size and development dependent on other factors (i.e. available resources, cultivar). However, if only one of the two ovules is fertilized then one side of the fruit may be underdeveloped compared to the other (Free 1993), and a significant number of these poorly pollinated fruit can be detrimental to crop value. Some research has suggested that cultivars that are capable of self-pollination will produce fruit of superior quality (shape) when cross-pollinated with another cultivar (Hassan et al. 2007).

Pollination Recommendations: Plums are self-incompatible, and a tree cannot be fertilized by its own pollen, or even the pollen of a tree of the same cultivar. As a general rule in tree fruit orchards, planting a pollenizer cultivar as every third or fourth tree in a staggered pattern will ensure that each main cultivar tree is adjacent to a pollenizer. Growers should confirm that their choice of pollenizer is suitable for cross-pollination with the production cultivar when planning an orchard (Fitzgerald 2005). Honey bees have been demonstrated to improve fruit set and yield in cultivated plum (Free 1962; Calzoni & Speranza 1998; Sapir et al. 2007), but problems and poor fertilization may arise due to the early flowering period in Ontario, when the weather is often inclement in the spring. Honey bees will not forage below 15C or if there is too much wind or dampness, and loss of time working the crop can have serious negative effects on fruit set and yield (Benedek & Nyeki 1996). The standard recommendation to facilitate pollination in plum is 2.5 strong colonies of honey bees per hectare, to be placed in the orchard when 30% of flowers are in bloom (Kevan 1988; Scott-Dupree et al. 1995; Slingerland & Lay 2007). The hive or domicile openings should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995; Delaplane & Mayer 2000; Slingerland & Lay 2007). It should be noted however that cold temperatures can also hamper the physiological process of pollen tube growth and fertilization, leading to problems with fruit set and seed production. Species such as bumble bees and blue orchard bees may be valuable for plum pollination during inclement weather, although research is necessary into their effectiveness for this particular crop (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Wild bees and possibly even flies are may also be valuable, particularly in small orchards adjacent to suitable wild habitat (Slingerland & Lay 2007), although specific management to increase their populations would be required in most situations (Scott-Dupree & Winston 1987).

Management of competing blooms in the orchard is an important concern in facilitating pollination, but must be undertaken with care and with the overall pollination strategy of the orchard in mind. If establishment of alternative pollinators such as the blue orchard bee are of interest to the grower, provision of alternative forage is required, in order that the bees have sufficient bloom resources to complete their life cycle and provide adequate nutrition. While both sufficiency of resources and nutrition are concerns for managed pollinators, it is important to avoid competition with the crop for pollination services in order to make most efficient use of those services. This is particularly important when the crop is less attractive to foraging insects than the weeds. Growers should mow (not herbicide) competing blooms during fruit bloom only. However, growers should also be aware that blossoms may attract bees to orchards off-bloom, which can result in bee kills if the grower uses insecticides (see Section 5.0).

3.2.4 Sweet Cherries (*Prunus avium*)

Mating & Breeding System: All flowers in genus *Prunus* are similar to those of apple and pear, except that they only possess one style and one ovary containing a pair of ovules. The flowers of most sweet cherry cultivars are self-incompatible, and require cross-pollination with pollen from an appropriate pollenizer cultivar and carried by insects in order to set fruit and produce seeds. There is also evidence that insects can have a significant effect on pollination of self-compatible cultivars by physically moving the pollen from anther to stigma (i.e. De Oliveira et al. 2001a). There are some cultivars available that are specially bred to be self-fruitful (i.e. Vandalay, Stella, Sonata; see Slingerland & Lay 2002). An extensive chart of cultivar compatability and bloom times was compiled by Choi et al. (2000), and covers a more extensive range than Ontario.

Pollination, Quality & Yield: Apart from those self-fruitful cultivars that do not seem to show improved yields in the presence of insect pollinators (Slingerland & Lay 2002), the transfer of pollen from a compatible pollenizer to the flower of the producing cultivar is essential for fruit set to occur. Pollenizers should be placed in such a manner that no production tree is more than two trees away from a suitable pollinizer, and insects are required to carry the pollen from the pollenizer to those blossoms. Early pollination is desirable, as some cultivars show loss of ovules beginning shortly after blooming (Eaton 1959, 1962). Hedhly et al. (2007) found that warm temperatures during bloom discouraged fruit set, suggesting that sweet cherry is adapted to an early fruit set in temperate climates. Because each flower contains only one pair of ovules, asymmetry of poorly pollinated fruit is less of a problem than in the pome fruits. If neither is fertilized, the flower will wither and drop, and if both are fertilized then the flower is fully pollinated and a symmetrical fruit is expected, with size and development dependent on other factors (i.e. available resources, cultivar). However, if only one of the two ovules is fertilized then one side of the fruit may be underdeveloped compared to the other (Free 1993), and a significant number of these poorly pollinated fruit can be detrimental to crop value.

Pollination Recommendations: Cherries are self-incompatible, and a tree cannot be fertilized by its own pollen, or even the pollen of a tree of the same cultivar. As a general rule in tree fruit orchards, planting a pollenizer cultivar as every third or fourth tree in a staggered pattern will ensure that each main cultivar tree is adjacent to a pollenizer. Growers should confirm that their choice of pollenizer is suitable for cross-pollination with the production cultivar when planning an orchard. The standard recommendation to facilitate pollination in sweet cherries is 1.5-5 colonies of honey bees per hectare, to be placed in the orchard by the time of first bloom (Kevan 1988; Scott-Dupree et al. 1995; Slingerland & Lay 2002).

However, because of the early bloom period of cherries, when frost and inclement weather is still a concern in Ontario and honey bees may not be willing to forage, research into alternative pollinators is warranted. Honey bees will not forage below 15C or if there is too much wind or dampness, and loss of time working the crop can have serious negative effects on fruit set and yield (Benedek & Nyeki 1996). The hive or domicile openings should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995; Delaplane & Mayer 2000; Slingerland & Lay 2002). Both bumble bees (see Section 2.1.2) and blue orchard bees (see Section 2.1.3) have demonstrated potential for pollinating early-blooming tree fruit crops, although research is necessary into their effectiveness for this particular crop in Ontario (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Bosch et al. (2006) studied blue orchard bee performance in a northern Utah cherry orchard, and found that populations of approximately 2000 female bees per hectare increased average yield 2.2 times over honey bees, despite poor weather during the bloom. Wild bees and possibly even flies are may also be valuable, particularly in small orchards adjacent to suitable wild habitat, although specific management to increase their populations would be required in most situations (Scott-Dupree & Winston 1987).

Management of competing blooms in the orchard is an important concern in facilitating pollination, but must be undertaken with care and with the overall pollination strategy of the orchard in mind. If establishment of alternative pollinators such as the blue orchard bee are of interest to the grower, provision of alternative forage is required, in order that the bees have sufficient bloom resources to complete their life cycle and provide adequate nutrition. While both sufficiency of resources and nutrition are concerns for managed pollinators, it is important to avoid competition with the crop for pollination services in order to make most efficient use of those services. This is particularly important when the crop is less attractive to foraging insects than the weeds. Growers should mow (not herbicide) competing blooms during fruit bloom only. However, growers should also be aware that blossoms may attract bees to orchards off-bloom, which can result in bee kills for neighbouring beekeepers if the grower uses insecticides (see Section 5.0).

3.2.5 Sour Cherries (*Prunus cerasus*)

Mating & Breeding System: All flowers in genus *Prunus* are similar to those of apple and pear, except that they only possess one style and one ovary containing a pair of ovules. Most cultivars of sour cherry are self-compatible, although insects may still play a significant role in moving pollen to receptive stigmata (Benedek et al. 2005).

Pollination, Quality & Yield: While sour cherry is self-fertile and does not require pollinizers in the orchard, the presence of honey bee colonies can increase yield by two- to four-fold if the orchard is large, or if the wild pollinator community is not sufficient. The flowers of sour cherries are not designed to be pollinated by wind, and the benefit of pollen movement by insects in the sheltered conditions of the orchard apparently improves productivity (Free 1993; Delaplane & Mayer 2000). Growers should note, however, that it is possible in self-compatible stone fruit crops for "over-pollination" to occur. If this happens, there will be a high yield by weight, but the trees attempt to mature too many fruits for the available resources with the result that a high proportion of fruit are undersized and therefore of reduced value. If over-pollination is a problem in a particular orchard, growers may wish to reduce or eliminate their use of supplementary pollination services.

Pollination Recommendations: The use of honey bees is considered "optional" with sour cherry, particularly if the wild pollinator populations in the orchard are healthy. If desired, the recommendation to facilitate pollination in sour cherries is 2.5-5 strong colonies per hectare, to be placed in the orchard by the time of first bloom (Scott-Dupree et al. 1995; Slingerland & Lay 2002). However, because of the early bloom period of cherries, when frost and inclement weather is still a concern in Ontario and honey bees may not be willing to forage, research into alternative pollinators is warranted. The hive or domicile opening should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995; Delaplane & Mayer 2000; Slingerland & Lay 2002). Both bumble bees (see Section 2.1.2) and blue orchard bees (see Section 2.1.3) have demonstrated potential for pollinating early-blooming tree fruit crops, although research is necessary into their effectiveness for this particular crop in Ontario (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Wild bees and possibly even flies are may also be valuable, particularly in small orchards adjacent to suitable wild habitat, although specific management to increase their populations would be required in most situations (Scott-Dupree & Winston 1987). If over-pollination is a problem in a particular orchard, growers may wish to reduce or eliminate their use of managed pollinators.

3.2.6 Apricots (*Prunus armeniaca*)

Mating & Breeding System: All flowers in genus *Prunus* are similar to those of apple and pear, except that they only possess one style and one ovary containing a pair of ovules. Most apricot cultivars are self-compatible and do not require planting with pollenizers, although there are some exceptions (i.e. Vivagold; Slingerland et al. 2002b; Milatovic et al. 2010). Insects may still play a significant role in moving pollen to receptive stigmata. Due to the climate in Ontario, there is a limited number of suitable cultivars that are available to growers, particularly new cultivars that have been developed for disease resistance (bacterial spot) and delayed bloom to avoid frost damage (Slingerland et al. 2002b). It would be beneficial to Ontario growers to evaluate self- and cross-compatibility of pollen in these cultivars.

Pollination, Quality & Yield: While apricot is self-fertile and does not require pollinizers in the orchard, the flowers of apricot are not designed to be pollinated by wind, and the benefit of pollen movement by insects in the sheltered conditions of the orchard may improve productivity. Growers should note, however, that it is possible in self-compatible stone fruit crops for "over-pollination" to occur. If this happens, there will be an overly heavy fruit set and high yield by weight, as the trees attempt to mature too many fruits for the available resources with the result that a high proportion of fruit are undersized and therefore of reduced value. Heavy fruit set can also result in physical damage to the trees. If over-pollination is a problem in a particular orchard, growers may wish to reduce or eliminate their use of supplementary pollination services.

Pollination Recommendations: Use of honey bees on apricot in Ontario is considered "optional", unless a self-sterile cultivar is being grown (Kevan 1988; Slingerland et al. 2002b). Honey bees could be effective in apricot, and 2.5 colonies per hectare is recommended if pollination is poor in an orchard (Scott-Dupree et al. 1995). Due to the early bloom period of apricot, when frost and inclement weather is still a concern in Ontario, the hive or domicile opening should face to the south, to facilitate warming in the morning and encourage bee activity (Scott-Dupree et al. 1995). Both bumble bees (see Section 2.1.2) and blue orchard bees (see Section 2.1.3) have demonstrated potential for pollinating such crops, although research is necessary into their effectiveness for apricot in Ontario (Bosch & Kemp 1999; Thomson & Goodell 2001; Bosch et al. 2006). Wild bees and flies are may also be valuable, particularly in small orchards adjacent to suitable wild habitat. Unless poor pollination is an evident problem in a particular orchard, growers may choose to avoid the use of managed pollinators.

3.2.7 Peaches & Nectarines (*Prunus persica*)

Mating & Breeding System: All flowers in genus *Prunus* are similar to those of apple and pear, except that they only possess one style and one ovary containing a pair of ovules. Most varieties of peach and nectarine are self-compatible, including fertilization within a single flower (autogamy) to a degree dependent on cultivar. Thus, pollenizers are not required for successful fruit set, and insects do not seem to play a significant role in moving pollen under most conditions (Slingerland & Subramanian 2007).

Pollination, Quality & Yield: Growers should note that it is possible in self-compatible stone fruit crops for "over-pollination" to occur. If this happens, there will be an overly heavy fruit set and high yield by weight, as the trees attempt to mature too many fruits for the available resources with the result that a high proportion of fruit are undersized and therefore of reduced value. Heavy fruit set can also result in physical damage to the trees.

Pollination Recommendations: Use of honey bees on peaches and nectarines in Ontario is considered "optional", and growers may wish to avoid the use of supplementary pollination services as overpollination may be an issue (Kevan 1988; Slingerland & Subramanian 2007). If poor pollination is an evident problem in a particular orchard, 1-2.5 colonies of honey bees per hectare may be used (Kevan 1988; Scott-Dupree et al. 1995). Bumble bees (see Section 2.1.2) and blue orchard bees (see Section 2.1.3) may also be considered, although there has been little research into the effectiveness of these species. Wild bees and flies may also be valuable, particularly in small orchards adjacent to suitable wild habitat. Unless poor pollination is an evident problem in a particular orchard, growers may choose to avoid the use of managed pollinators.

3.3 Small Fruit

3.3.1 Currants & Gooseberries (*Ribes* spp.)

Mating & Breeding System: This genus contains numerous species of berries that are cultivated or collected from the wild, in addition to cultivated representatives. Most are monoecious, with perfect flowers. In black currant (*R. nigrum*) almost all cultivars require insect pollination, due to the physical distance between style and anthers in individual flowers. Although cultivars are at least somewhat self-compatible, insect cross-pollination is required in order to set a satisfactory crop (Denisov 2003).

Gooseberry (*R. uva-crispi*, also American hairystem gooseberry *R. hirtellum*) also show some evidence of self-incompatibility in pollinator exclusion experiments, although the effect in most cultivars is considerably less than in black currant. As in black currant, the structure of the flower (inverted position, anthers laterally distant from stigma) is such that spontaneous selfing appears to be discouraged. The mating system of red currant (*R. rubrum*) has been considerably less studied, but shows a similar ability to self and benefit of cross-pollination as the previous two species discussed.

Pollination, Quality & Yield: Pollination strongly affects yield in these crops, as berries with no or few fertilized ovules will be shed early in the season (Wellington et al. 1921). Under some conditions, however, fertilized ovules may abort before completing development. In this phenomenon, known as *fruit drop* or *running off*, self-pollinated fruits appear to be selectively aborted, apparently to conserve resources in favour of cross-pollinated fruits (Szklanowska & Dabska 1993). Lack of pollination can also reduce the size and weight of individual berries (Teaotia & Luckwill 1956) in black currant. Research has shown that the presence of insects, particularly bees, significantly improved proportional fruit set, mature fruit produced, and the size and number of seeds in mature *Ribes* fruit (Zakharov 1958; Jefferies et al. 1982; Szklanowska & Dabska 1993). Cross-pollination has been shown to improve proportional fruit set, fruit size, yield, and number of seeds per fruit. The same is true for at least some gooseberry cultivars, which demonstrate a two- to three-fold improvement in yield, including number, size, and weight of individual berries, when pollinating insects have access to the flowers.

Pollination Recommendations: Both honey bees and wild bees are effective pollinators of black currant, attracted by the nectar which varies in concentration with cultivar (Koltowski et al 1999). The use of honey bees for pollination in Ontario must take the season into account, particularly for gooseberry which flowers early and in cold and damp weather conditions that may deter honey bees (Eaton & Smith 1962). Generally, honey bees are recommended for pollination of *Ribes* crops (Dale & Schooley 1999). Four honey bee hives per hectare have been recommended by Blasse & Hofmann (1988) for red currant in Europe, and Scott-Dupree et al. (1995) recommend 2.5-5 colonies per hectare on black currant in Ontario.

3.3.2 Raspberries & Blackberries (*Rubus* spp.)

Mating & Breeding System: This genus contains numerous species of berries that are cultivated or collected from the wild, such as red raspberry (*Rubus idaeus*, *R. strigosus*, *R. occidentalis*) and blackberry (*R. fruticosus*). The flowers are actually groups of small flowers attached to a receptacle, that open in sequential rings beginning at the base over a period of a few days. Each inflorescence therefore has numerous stamens and styles, each attached to a carpel containing two ovules. Because the flowers on each receptacle open over an extended period, each inflorescence must be visited several times to ensure that individual flowers are pollinated if a marketable fruit is to develop. Following fertilization, the carpels develop into the fruit, each containing a seed, and together cover the receptacle. The genus is a large one, and there are many wild species and hybrids, many of which are self-infertile or dioecious, and therefore require cross-pollination by insects. Most cultivated varieties are hermaphroditic and self-fertile.

Pollination, Quality & Yield: Some cultivated varieties have shown no difference or even a negative effect of cross-pollination on fruit set and mean fruit weight when compared to self-pollination (Hardy 1931). However, most evidence suggests that insect pollinators are beneficial to the crop, in that more flowers set fruit, there are more seeds per fruit, and/or fruits are better formed and heavier, all of which leads to greater yields (Johnston 1929; Couston 1963; Shanks 1969; De Oliveria et al. 1984). Cross-pollinated flowers are more likely to develop fruit to maturity. Chagnon et al. (1991) found that 5-6 honey bee visits totalling about 150 seconds was sufficient for pollination of raspberry. Activity of pollinators that is too high may also be an issue, particularly with bumble bees, as their foraging activity may become aggressive, damage the flowers and cause deformities in the resulting fruit.

Pollination Recommendations: Cultivated species of *Rubus* produce abundant nectar and are attractive to a broad spectrum of pollinating insects (Whitney 1984; Willmer et al. 1994). The flowers are shallow and easily accessible to most pollinators, and 1-2.5 or more colonies per hectare of managed honey bees are recommended for the crop (Kevan 1988; Scott-

Dupree et al. 1995). Bumble bees have also been identified as effective pollinators, even superior to honey bees in some cases. Working with *R. idaeus* in Scotland, Willmer et al. (1994) found that bumble bees outperformed honey bees in floral constancy, speed, longer foraging time per day, and willingness to forage in poorer weather. However, Lye et al. (2011), also working in Scotland, found that the benefit from commercial bumble bee colonies was small, because it was possible for the wild bee populations to be adequate. The potential for bumble bee pollination, both wild and managed, should be investigated in Ontario. There has also been investigation into the use of one species of solitary mason bee (*Osmia aglaia*) in western North American *Rubus* plantations affected by pollination deficits (Cane 2005).

3.3.3 Strawberries (*Fragaria* x *ananassa*)

Mating & Breeding System: The cultivated strawberry is a hybrid of North and South American wild strawberries, the former (*Fragaria virginiana*) selected for flavour, the latter (*Fragaria chiloensis*) for large size. Many cultivars are self-fertile with hermaphrodite flowers, each of which is actually a large group of tiny flowers (inflorescence) clustered on a receptacle. In this respect, the flowers are similar to those of *Rubus* (Section 3.3.2), but in strawberry it is the receptacle itself that develops into the fruit tissue, with the seeds from fertilized flowers borne on the outer surface. The pistils often mature well before the anthers on a given receptacle, although when the anthers mature self-pollination can occur to fertilize any remaining ovules on that receptacle. Some flowers, however, lack stamens, have few stamens, have stamens that produce little or no pollen, or have some sterile pistils, resulting in self-sterility or sterility of some flowers within an inflorescence. These problems have largely been corrected in modern cultivars through breeding programs. In these, insect pollination is essential to carry pollen from other flowers. Pollination in commercial fields likely results from a combination of wind and pollinator action delivering both self- and cross-pollen to inflorescences, although the comparative value of each in fertilization and fruit development is unclear (Allen & Gaede 1963; Bagnara & Vincent 1988; Chagnon et al. 1993; Zebrowska 1998).

Pollination, Quality & Yield: An individual strawberry flower is composed of numerous tiny fruits on a conical receptacle, each with its own pistil. Full pollination of all fruits is required for the best quality product. Open pollination of flowers by insects has been demonstrated to increase fruit set, yield, and quality of fruit (Bagnara & Vincent 1988; Chagnon et al. 1989, 1993; Zebrowska 1998). The more flowers on the receptacle that are pollinated, the greater the size of the fruit, and if unpollinated flowers are grouped a misshapen berry will result, as the receptacle near unfertilized ovules will not develop. As many as 20 bee visits per receptacle is required to fully pollinate all of the flowers sufficiently to produce a marketable fruit, and incremental increases in final berry weight can be seen with as many as 60 visits (Skrebtsova 1957), as flowers on a given receptacle become receptive over an extended period of time. This level of pollination service may require as many as seven or more days to occur (Antonelli et al. 1988). Activity of pollinators that is too high may also be an issue, particularly with bumble bees, as their foraging activity may become aggressive, damage the flowers and cause deformities in the resulting fruit. Chagnon et al. (1989) found that honey bees do an adequate job of pollination when wild bees are uncommon, but played a complementary role when wild bees were common, with honey bees pollinating apical flowers, and smaller wild bees working basal flowers on a given inflorescence (Chagnon et al. 1993; Albano et al. 2009).

Pollination Recommendations: Although some strawberry cultivars are self-fertile, the role of self-pollination, which largely occurs from the same flower in cultivars with perfect flowers, and which generally cannot occur in those with imperfect flowers without insect activity, in producing marketable fruit is not clear. There is some evidence that self-pollen can have a negative effect on fruit size, weight, and shape when compared to cross-pollen (Free 1968; Colbert & De Oliveira 1992; Zebrowska 1998). Thus, the use of pollenizers (cultivars that have abundant staminate flowers, and are different from the primary cultivar) is encouraged, in a minimum ratio of 1:5 with the primary cultivar. Growers should pay close attention to the availability of pollinators, although unless the fields are a particularly large monoculture or lack healthy wild pollinator populations supplementation with rental honey bees are not necessary. Recommendations are vague, ranging from 0.5-2 colonies per hectare to 20 or more in some cases (Kevan 1988; Scott-Dupree et al. 1995). Clearly, research on the quantitative role of honey bees and optimal stocking rates in Ontario strawberry crops are required. Furthermore, strawberry flowers may not be as attractive to honey bees as many competing blossoms, which may necessitate mowing of adjacent vegetation at the appropriate time. In greenhouses, the use of suitable bees or pollinating flies (drone flies, blow flies) is required to give quality crops in terms of size and weight of fruit, and minimizing the proportion of misshapen fruit. Syrphid flies, particularly large-bodied species such as the drone flies (*Eristalis*), have also been observed effectively pollinating strawberry in the field (Albano et al. 2009).

3.3.4 Highbush blueberries (*Vaccinium corymbosum*, and others)

Mating & Breeding System: *Vaccinium* is a large genus of plants with numerous cultivated species (see also Section 3.3.5, below). While the species of lowbush blueberries are highly important crops in other parts of Canada, in Ontario the great majority of cultivated blueberries are highbush species (*V. corymbosum*, also *V. australe*, *V. atrococeum*). Blueberry flowers are bell-shaped and pendant, and generally pollination is effected only by bees, largely due to the need for "buzz pollination" in which the foraging bee grasps the stamens with its mandibles and rapidly vibrates its flight muscles in order to free the pollen through the small pores in the anthers. Not all bees are capable of this type of action, and therefore may be ineffective at pollination of the blueberries. Honey bees are able to "drum" on the anthers with their legs and collect some pollen, although considerably fewer grains per visit than those species that buzz pollinate. Some varieties (i.e. Bluecrop) have been found to be self-compatible and do not show a significant improvement due to cross-pollination, although this may not be true for all varieties, and more testing is required to determine which varieties perform best with a pollenizer variety nearby (MacKenzie 1997; Ehlenfeldt 2001). Cross-pollination is generally the rule, however, as male and female structures tend to mature at different times within a given flower, and the pendant form of the flower discourages selfing through wind or gravity.

Pollination, Quality & Yield: Benefits of insect pollination include a greater proportion of flowers producing marketable fruit, and more seeds per berry resulting in larger berries, although this observation does not hold across all varieties. The quantity of pollen delivered by pollinators improves fruit set, fruit weight, and number of viable seeds, although it does not seem to matter if the pollen is self or cross in at least some cultivars (Vander Kloet 1991; Dogterom et al. 2000). However, Huang et al. (1997) working with *V. corymbosum* in the southern United States found that self-pollinated flowers were more likely to abort, or to have poorly developed ovules, than those that were cross-pollinated. Some varieties have the best reproductive success associated with smaller berries, and some are *parthenocarpic*, producing fruit without pollination or seed production (MacKenzie 1997). Many of these berries, however, are not marketable. Total fruit set is similar whether wild or managed bees are providing pollination services, and is positively correlated with bee abundance (Isaacs & Kirk 2010). Ratti et al. (2008) also found that individual blueberry mass was positively correlated with bee abundance, but not bee diversity. Individual berries in large fields, likely pollinated by honey bees, have been observed to be considerably larger in some cases than in small fields (Isaacs & Kirk 2010). Seed number, not necessarily seed weight, is positively correlated with size of individual berries.

Pollination Recommendations: Honey bees are not capable of buzz pollination, lacking the ability to disengage their flight muscles from the wings in order to vibrate them. Thus, they generally do not seek pollen from blueberry, and pollen collected or transferred by the honey bees is incidental to their nectar foraging activities. When using honey bees, the number of hives used per hectare depends on the variety of blueberry (from 1-7.5 per hectare), and hives should be placed at 5-25% of full bloom (Kevan 1988; Pritts & Hancock 1992; Scott-Dupree et al. 1995). Bumble bees and numerous other species of wild bees are the most effective pollinators of blueberry. A diversity of wild bee species are routinely active in highbush blueberry fields during the bloom, many of which visit and deliver pollen to blueberry flowers (MacKenzie & Eickwort 1996; Ratti et al. 2008; Tuell et al. 2009). The effectiveness of wild pollinators may be limited by the ratio of edge habitat to the area of the blueberry field, because they will only travel a short distance from habitat containing their nesting sites and other resources. Wild bees can provide the majority of pollination service in small fields, but play a much-reduced role in larger fields supplied with honey bees (Isaacs & Kirk 2010). Blueberry growers are encouraged to provide blooming alternate forage, particularly those flowering before and after the blueberry, at their field edges, and even in the middle of large fields (Walton & Isaacs 2011). Furthermore, artificial nesting sites such as bundle of reeds, drilled wooden blocks, and untilled dry soil can increase wild bee populations in the long term. Investigation into the biology and life history of *Vaccinium*-specialist bees, which may be abundant at some sites, may prove especially fruitful (MacKenzie & Eickwort 1996).

3.3.5 Cranberry (*Vaccinium macrocarpon*)

Mating & Breeding System: Cranberry is dependent on insect pollination for reproduction, with very little marketable fruit setting in the absence of pollinator activity. Young flowers release pollen which is picked up by nectar foragers probing into the flower. That pollen will be transferred to the stigma of an older flower, exhausted of pollen but still providing a nectar resource. In individual flowers, the pollen is shed approximately 1-2 days prior to the stigma becoming receptive. Cross-pollination is the rule, as male and female structures tend to mature at different times within a given flower, and the pendant form of the flower discourages selfing through wind or gravity. Reproductive stems will generally abort excess flowers leaving an average of three per flowering stem even when pollinated, because they lack resources to mature all of the fruit (Sarracino & Vorsa 1991; Brown & McNeil 2006).

Pollination, Quality & Yield: The need for insect pollinators is well-known, with fruit set in the absence of pollinators shown experimentally to be less than 10% of the potential, increasing several-fold in their presence. Cross-pollination also results in larger fruit with more seeds, and there is evidence that self-pollinated flowers will abort their seeds in favour of cross-pollinated flowers (Sarracino & Vorsa 1991). In commercial plantations, honey bees are associated with sufficient pollen delivery for optimal fruit set, production of larger berries, and more even pollination across the bog (Evans & Spivak 2006).

Pollination Recommendations: Cranberry is not a strong producer of either pollen or nectar for foraging insects (Delaplane & Mayer 2000). If the pink colour of the flower intensifies with age, it indicates poor pollination, and can serve as an indicator across an entire crop (Delaplane & Mayer 2000). Ratti et al. (2008) found that individual cranberry weight was positively correlated with bee abundance, but not bee diversity. Although honey bees are not capable of buzz pollination, lacking the ability to disengage their flight muscles from the wings in order to vibrate them, this drawback does not seem as great as with other flowers with poricidal anthers (i.e. tomato, blueberry) as honey bees can effectively extract pollen by drumming or stroking the anthers. Usually, however, pollen collected or transferred by the honey bees is incidental to their nectar foraging activities. Because honey bees are not enthusiastic foragers on cranberry, a recommendation of 2.5-7.5 hives per hectare is given for sufficient pollination. This broad range may reflect the variation in yield associated with the strength of wild bee populations near the bog (Kevan 1988; Scott-Dupree et al. 1995; Delaplane & Mayer 2000).

Numerous wild bees are observed visiting cranberry in many areas where it is grown, typically 25-30 species in a given area, although if honey bees are present they often numerically dominate the foragers (Kevan et al. 1983; MacKenzie & Averill 1995; Evans & Spivak 2006; Broussard et al. 2011). Large bees such as bumble bees are the most effective pollinators of cranberry (Kevan et al. 1983; Mohr & Kevan 1987; MacKenzie 1994; Cane & Schiffhauer 2003; Loose et al. 2005; Ratti et al. 2008). In large bogs, however, wild pollinators may not provide adequate service and honey bees or bumble bees should be added (Delaplane & Mayer 2000; Evans & Spivak 2006). Competing blooms at the field edges should be mowed when cranberry is blooming, but can provide valuable resources for wild pollinators at other times, and growers are encouraged to provide alternate blooms, particularly those flowering before and after the crop, at their bog edges. The effectiveness of wild pollinators depends on the ratio of edge habitat to the area of the bog, because they will only travel a short distance from their nesting habitat (Filmer & Doehlert 1959; Loose et al. 2005; Evans & Spivak 2006). Artificial nesting sites such as bundle of reeds, drilled wooden blocks, and untilled dry soil can also be provided to increase wild bee populations in the long term. The leafcutter bee *Megachile addenda* has been demonstrated to be an excellent cranberry pollinator in the eastern United States, although difficult to rear on a commercial scale due to issues of parasitism (Cane et al. 1996; Cane & Schiffhauer 2003; Loose et al. 2005).

3.4 Forage, Cover Crop, & Green Manure Legumes

3.4.1 Alfalfa (*Medicago sativa*)

Mating & Breeding System: Alfalfa is a commonly grown forage plant, and seed is produced for propagation of forage crops, in addition to more specialized uses such as alfalfa sprouts for human consumption. Most Canadian production of alfalfa seed occurs on the prairies, particularly Saskatchewan. Alfalfa flowers are typically leguminous (see Section 1.2), with a 5-petal formula, the lower two petals modified into a "keel" that encloses the reproductive organs. Pollinators of these flowers must have the strength and ability to force their way between the keel petals to access nectar and pollen. The stamens are held under some tension and when the foraging action of a flower visitor trips the flower, the pistil and stamens, which are grouped together in a column, forcefully strike the underside of the head of the insect (Bohart 1957). Pollen is thus deposited in this area, which is likely to contact the stigma of other flowers that the insect visits, and which may be dislodged by the force of future trippings. Tripping of the flower also causes the breakage of a membrane on the stigma, which is required for pollen germination and subsequent fertilization to occur (Brink & Cooper 1936; Bohart 1957). Alfalfa may be self-incompatible, or pollen may be self-compatible to varying degrees. Because the pollen is deposited in the vicinity of the stigma within the enclosed keel, which is typical of legumes, if cross-pollen is not deposited when the flower is tripped fertilization may still occur (Bohart 1957; Brown & Bingham 1994).

Pollination, Quality & Yield: A flower has 10-12 ovules, although only a small proportion typically develop into seed. More seed will be produced under cross-pollination than self-pollination, but a flower must always be tripped, and therefore must be visited at least once if seed is to be set. High yields can be achieved, although it is difficult to assure sufficient pollination to do so (Free 1993). Although individual plants range across the full spectrum of self-compatibility, cross-pollination has been shown to result in more pods and more seeds per pod than self-pollination, even in fully self-compatible individuals. Brown & Bingham (1994) found that progeny resulting from self-pollination were less competitive and had lower survival under field conditions than did progeny from cross-pollinations, which demonstrates that poor pollination of the parent crop could be a quality concern for seed planted to forage.

Pollination Recommendations: The development of husbandry of the alfalfa leafcutter bee restored seed productivity to large fields, although the industry is currently recovering from difficulties related to bee health and culture under high population density (see Section 2.1.4). There is recent evidence that having bee densities that are too high for the available floral resources can be detrimental to both bee reproduction and alfalfa seed production (Pitts-Singer & Bosch 2010), so it is important not to introduce too many alfalfa leafcutter bees to a given field. Recommended stocking rates are 15-50 thousand cocoons (bees) per hectare, depending on conditions and bee availability (Kevan 1988; Scott-Dupree et al. 1995). Effectiveness of the bees can be greatly improved by timing their deployment correctly with the beginning of the bloom, but this is difficult because it must be anticipated by 2-3 weeks in order that the emergence process can be initiated.

Honey bees are generally reluctant pollinators of alfalfa, due to their apparent aversion to being struck forcefully in the head with the stamens when the flower is tripped. Honey bees also learn to forage for nectar on the flowers without tripping them, thereby circumventing the pollination mechanism by not touching the flower in the appropriate way (Brunet & Stewart 2010). If very high densities of bees are used (12 colonies or more per hectare are recommended, depending on location), they are capable of effecting pollination, and produce a desirable honey in the process. Efforts to selectively breed cultivars with characteristics less daunting to bees (stamens that protrude beyond the keel, keel petals that are not tightly closed), plants that can be tripped by smaller bees, or plants with higher nectar production, have yielded some satisfactory results (Free 1993). Many wild bees are highly effective pollinators of alfalfa, and can play a significant role if fields are small and suitable habitat exists for them (Fischer 1953; Bohart 1957; Brunet & Stewart 2010).

3.4.2 Clover (*Trifolium* spp.)

Mating & Breeding System: Clovers are important crops for numerous reasons, having high value as livestock forage, green manure and cover crops, and also as honey plants. Commercial production of clover seed requires high pollinator activity, and typically makes use of honey bee pollination services. Red clover (*Trifolium pratense*), white clover (*T. repens*), and alsike clover (*T. hybridum*) are the major species found in Ontario forage crops, although numerous other species of *Trifolium* are cultivated in various parts of the world. The flowers of clover follow the typical legume structure although the individual tubular flowers are small, narrow, and grouped together in inflorescences. The anthers dehisce and release the pollen inside the bud prior to opening. The weight of a flower visitor exerts pressure on the standard and wing petals, and causes the anthers and stigma to extend forward and press against the underside of the head of the visitor. Unlike many other legumes, small visitors are capable of pollinating the small individual clover flowers (Turkington & Burdon 1983). Following a visit, the sexual structures return to their original position, allowing the same flower to deliver pollen repeatedly (Bohart 1957). It is generally thought that all three species of clover are self-sterile, although there are varieties that are self-fertile, particularly in white clover. The action of insects is required for successful seed set. Manipulation of the flowers causes pollen to be deposited on the ventral surface of the visitor, at the same time as the stigma is contacted and cross-pollen delivered.

Pollination, Quality & Yield: Alsike and red clovers require long-tongued bees for pollination, due to the depth of the corolla tube these are the only insects that can reach the nectar. Although long-tongued, honey bees exhibit difficulty accessing the minute portions of available nectar, whereas smaller insects may be able to access the pollen. Yield of alsike clover is improved 10-fold or more when insect pollinators have access to the flowers, and it has been suggested that many crops are under-pollinated and could further improve production (Dunham 1939).

Red clover is predominantly pollinated by bumble bees, as the tongues of honey bees are too short to reach the nectar resources easily in red clover unless the nectar levels are especially high. The foraging rate of honey bees may be slowed considerably compared to bumble bees, as they must force their heads into the blossoms (Woodrow 1952; Hawkins 1969). However, honey bees will still collect pollen from red clover under some circumstances, but their role and reliability in red clover pollination as it relates to ease of nectar access requires further investigation (Wermuth & Dupont 2010). Short-tongued bumble bees will commonly rob the clover species with long corollas, particularly red clover, and can have a negative effect on seed production. Several studies have found that bumble bees and honey bees had similar pollination performance on red clover in Oregon, and identified the value in conservation of wild bees, including bumble bees, in addition to honey bee rentals for seed production (Rao & Stephen 2009; Wermuth & Dupont 2010). Some researchers have found significant increases in yield of seed crops with honey bee colonies added (i.e. Peterson et al. 1960), and there have been efforts to breed red clover with shorter corolla tubes that will allow a broader spectrum of visitors, including honey bees, access to the nectar. Pollinated flowers soon wilt and lose their colour, so a field full of colourful, blooming flower heads is an indication of poor pollination.

White clover has much shallower florets, allowing a wider variety of insects to access the nectar and serve as pollinators. Florets begin to wilt following pollination, so an overabundance of fresh florets, or infloresences composed mostly of receptive florets are indications of poor pollination. Similar to the other clover species, bee pollination greatly increases the seed yield of white clover, giving 30-fold or more increases (Goodman & Williams 1994). Turkington & Burdon (1983) report that the most important determinants of seed yield are the availability of pollinators and weather conditions during bloom, which interact due to both effects of weather on pollinator activity, on nectar production, and on physiological fertilization factors.

Pollination Recommendations: Placing commercial honey bees on the fields is the standard practice for clover pollination, and produces a highly desirable honey in the process. However, in commercial production fields there are so many blooms that full pollination may be prohibitively expensive in honey bee rentals. Clover species have desirable resources for honey bees, but they require considerable effort to access. Research has shown that wild bees also play a role in pollination, and are responsible for some of the seed set (Green 1956, 1957). Wild bees, especially long-tongued bumble bees but also long-tongued megachilids are effective pollinators (Fairey & Lefkovitch 1993a,b), but are rarely present at sufficient abundance to pollinate commercial fields. It has been demonstrated that micronutrients, particularly boron, has a strong influence on nectar production, which in turn can significantly influence pollinator visits and seed production (Johnson & Wear 1967; Smith & Johnson 1969). Growers with poor pollination may wish to contact OMAFRA to arrange a soil test.

For alsike clover, recommendations are 2.5-8 honey bee colonies per hectare for adequate pollination (Fischer 1954; Dunham 1957; Kevan 1988; Scott-Dupree et al. 1995). The alfalfa leafcutter bee (Section 2.1.4) has been observed to be an effective pollinator of alsike clover (Fairey & Lefkovitch 1993a), and reproduced well using resources from red clover (Holm 1984). Bumble bees are rarely present in sufficient numbers to pollinate clover at cultivated scales, but their encouragement is recommended due to their effectiveness, particularly on red clover when honey bees have difficulty extracting resources (Bohart 1957; Holm 1966). Addition of honey bees at a rate of 2.5-10 colonies per hectare is recommended in large fields, as they can significantly improve seed yield (Scott-Dupree et al. 1995). Development of bumble bee culture in red clover is also worth investigating, rather than adding more honey bees, due to the efficiency of bumble bees foraging on the deep red clover florets (Holm 1966; Kevan 1988). For white clover, honey bee stocking recommendations are 1-8 honey bee colonies per hectare (Weaver 1957; Oertel 1961; Kevan 1988; Scott-Dupree et al.

1995). However, there is great potential for additional pollination to increase seed production in a given field, and beekeepers with an interest in production of clover honey may be interested in increasing hive deployment on any of the clover species.

Species of sweet clover, which may also be grown for seed in Ontario, are not true clovers but are legumes in the genus *Melilotus*. However, honeybee stocking recommendations are similar at 2.5-8 colonies per hectare (Kevan 1988; Scott-Dupree et al. 1995).

3.4.3 Crown vetch (*Coronilla varia*)

Mating & Breeding System: Crown vetch is a non-native legume that has found extensive use in North America in such uses as erosion control and land rehabilitation, due to its mat-forming growth habit and its ability to grow well under extremely poor soil conditions. It is also a quality source of pollen and nectar for foraging pollinators. Crown vetch is self-incompatible, and dependent upon insect pollination to produce seed (Cope & Rawlings 1970). Many bees, including honey bees, bumble bees, and solitary bees are common visitors, although achieving adequate pollination at a commercial scale is difficult.

Pollination, Quality & Yield: All flowers do not contain nectar, although bees can forage for nectar without tripping the flowers because nectaries are located external to the blooms. Only large, strong bees can trip the flowers and forage for pollen. Addition of managed honey bees gives an acceptable seed yield, and in suitable habitat wild bumble bees and other bees may do a passable job.

Pollination Recommendations: Honey bee colonies can be moved onto crown vetch, although experiments have shown that it is not a favoured crop, and they will often leave for different forage within a short period of time. Honey bees apparently have a difficult time learning to manipulate the flowers in order to access pollen, which is a more complex process in this species than in other legumes (Anderson 1959). Bumble bees can visit more flowers, and are capable of tripping the flowers more easily to collect pollen, but are rarely abundant foragers on this crop. Because it takes a long time (50 days) for seed to mature, it is recommended that pollination be initiated as early in the season as the bloom will allow (Al-Tikrity et al. 1974). As many as 10 colonies per hectare are recommended for seed production (Kevan 1988). The alfalfa leafcutter bee (*Megachile rotundata*) has demonstrated an affinity for crown vetch pollen (Horne 1995), and investigation into its utility as a managed pollinator for the crop may be worthwhile.

3.4.4 Birdsfoot-Trefoil (*Lotus corniculatus*)

Mating & Breeding System: Birdsfoot-trefoil (also known as broadleaf trefoil) is a legume, with a floral structure typical of that family (see Section 1.2). It is is largely self-incompatible, and dependent upon insect pollination to produce seed, although some varieties will set a small number of self-pollinated seeds particularly if the keel is depressed (for instance, by rain). While self-pollination is therefore possible, in practice the activity of insects is required to move pollen appropriately for fertilization (Turkington & Franko 1980). Only large, strong bees can trip the flowers and successfully pollinate, and pollination by other insects appears to be negligible (Morse 1958; Bader & Anderson 1962; Murrel et al. 1982). The anthers dehisce within the flower before it opens, depositing the pollen in the vicinity of the stigma, within the keel. The flowers lack a tripping mechanism, but are designed to deliver a dose of pollen over multiple visits. During each visit a quantity of sticky pollen is pushed out of the keel and adheres to the ventral surface of the visitor (Turkington & Franko 1980). There is some indication that suitable cross-pollen may be more likely to set seed than self-pollen, or cross-pollen from a closely related plant (Miller 1969; Dobrofsky & Grant 1980).

Pollination, Quality & Yield: Without visits from bees, few flowers set fruit and seed production is very low (Free 1993), and pollinators are therefore required for commercial seed production. A flower can be pollinated after a single bee visit, although as many as 25 visits to each flower is required for full pollination and maximum seed set (Morse 1958). The seed pods of the crop are dehiscent, which causes serious problems when trying to harvest a large crop, as much of the seed is lost through this dehiscence.

Pollination Recommendations: Bees collect both nectar and pollen from the flowers, and there has been some research into high-nectar cultivars in an effort to increase bee visits (Murrel et al. 1982). Morse (1958) found that honey bees were the dominant visitors of birdsfoot-trefoil, and readily pollinated it, and no more than 2.5 colonies per hectare are recommended, with any more being superfluous to pollination requirements. However, others recommend as many as eight colonies per hectare for growers in Ontario (Smith 1960; Kevan 1988; Scott-Dupree et al. 1995). The plant produces abundant, concentrated nectar, and is considered a valuable honey plant in North America (Free 1993).

3.4.5 Lupine (*Lupinus* spp.)

Mating & Breeding System: Lupines are legumes, with a floral structure typical of that family (see Section 1.2), and anthesis occurs and deposits the pollen within the keel before the flower opens. Some species are self-compatible, and in some of these pollination occurs within the flower before it opens (i.e. *Lupinus albus*; Williams et al. 1990). However, in at least some autogamous lupines reproductive output can be improved by pollinator action (Karoly 1992). In species where cross-pollination is the norm, the stigma is located in the tip of the keel well beyond the anthers, and therefore does not contact its own pollen. An insect of sufficient weight landing on the flower will push open the keel and contact the stigma and the pollen within. Several species of lupines may be grown as a forage or a nitrogen-fixing cover crop, and many more are grown as ornamentals. An important resource for pollinators, lupines also have potential in pollinator management and conservation applications. Bigleaf lupine (*L. polyphyllus*), for example, has been recommended as an alternative forage in orchards in eastern Canada, as it is attractive and provides abundant resources for managed and wild bees, but not at a time that competes with the fruit tree bloom (Sheffield 2008b). This type of forage is critically important for pollinating insects, which cannot complete their life cycles and maintain population levels between generations during the bloom period of a single crop, such as an orchard fruit.

Pollination, Quality & Yield: Honey bees and bumble bees are effective pollinators of lupine in those species that require it, and can collect considerable quantities of pollen and nectar from the plants. There is evidence that bee visits improve seed set by increasing both self- and cross-pollination, although the question needs to be further investigated for many species. In some species, honey bees may not be capable of tripping or opening large early flowers (although may do so with smaller flowers later in the season), and larger bees are required to enter the keel and access the resources (Forbes et al. 1971).

Pollination Recommendations: Cultivated lupine is generally taken to be self-fertile, and thus does not require additional pollinators to set a seed crop (Kevan 1988). Honey bees readily work lupine, and placing commercial honey bees on the fields produces a highly marketable honey in the process. Large bumble bees can easily trip the flowers, sometimes damaging them and permanently exposing the stigma so that smaller bees can enter the flower and pollinate (Leuck et al. 1968; Forbes et al. 1971). Since there is evidence that pollinator activity can be important for some lupine species, even improving the reproductive output of self-compatible species (Karoly 1992), research is required into reproductive details of cultivated species.

3.5 Oilseeds

3.5.1 Canola (*Brassica* spp.)

Mating & Breeding System: Canola has its origins in breeding programs of *Brassica napus* (oilseed rape) that were designed to reduce the concentration of glucosinolates and erucic acid, allowing for its development as a human food crop rather than only an industrial crop. Today, rather than being a single species, canola is more properly termed a complex of three species in the mustard family (Brassicaceae), together with various hybrids, biotypes, and cultivars. Considerable research effort into developing new types and hybrids of canola is expended by seed companies, although the pollination requirements for hybrid seed production are considerably different from those of the grower producing commodity canola. Canola is also of importance to apiculture, as it is the largest user of commercial honey bee pollination services in Canada. Most Canadian canola production occurs in the prairie provinces, but there is still a considerable quantity cultivated in Ontario, particularly in the northwest of the province. Despite consuming such prodigious quantities of pollination services, pollination requirements in canola remain a complex problem and are incompletely understood.

The species complex that is modern canola includes *B. rapa* (also known as *B. campestris*, a name now suppressed; turnip rape, or canola), *B. napus*, and *B. juncea* (Indian brown mustard). While the former species is diploid and the latter two species tetraploid, all three species share a set of paired homologous chromosomes that allows them to readily hybridize with each other. Of the three, only *B. rapa* is believed to be fully self-incompatible, with *B. napus* and *B. juncea* demonstrated to set seed readily without the intervention of insects. Genetically, most of the canola currently grown in Canada is spring canola, which is the self-compatible *B. napus*, although canola breeders are eager to investigate further hybridization with other species with desirable qualities such as herbicide resistance and oil quality (i.e. Iqbal et al. 2011). As commercially developed hybrid canola seed becomes more widely used, however, the questions may have to be revisited. Also at issue are differences in seed and oil quality in cross-pollinated versus self-pollinated seeds, which have not been fully investigated (Kevan & Eiskowitch 1990).

Pollination, Quality & Yield: There are many questions regarding canola pollination, compatibility, yield, and product quality that remain to be answered. Canola is an excellent honey plant, producing large quantities of concentrated nectar that is readily collected by honey bees, and pollen that is high in protein (Kevan et al. 1991b; Davis et al. 1998; Westcott & Nelson 2001). It has great nutritional benefits for bees, strengthening colonies that are weak and helping them fight disease (Westcott & Nelson 2001). However, beekeepers must watch the hives carefully for overpopulation and swarming concerns. Honey made from canola nectar crystallizes easily and may be difficult to remove from the combs with conventional automated methods, causing problems for beekeepers (Kevan et al. 1991b; Westcott & Nelson 2001). Honey bees have been demonstrated to increase yield substantially in some canola crops. Investigations of seed production of self-compatible *B. napus* consistently record increases in seed yield in fields supplied with honey bee colonies (one to seven per hectare) over fields with no bees (Sabbahi et al. 2005; Duran et al. 2010). Studies in Australia have observed increases in yield with honey bees added, or reductions if insects were excluded, resulting in increased yield in terms of total seed weight and seed number, although size of individual seeds was reduced (Langridge & Goodman 1975; Manning & Wallis 2005). Wild bees also seem to play a significant role in canola pollination, with greater yields and profitability correlated with quantities of available pastureland or wild areas available as bee habitat (Morandin & Winston 2005; Turnock et al. 2006). The presence of insect pollination has been observed to increase yield, but not to affect seed quality in terms of oil or protein content (Sabbahi et al. 2005; Oz et al. 2008).

Canola pollen can travel appreciable distances on the wind, and the relative role of wind and insects in pollination is not fully understood. Typically, insect pollinated plants have pollen with large, sticky grains, while wind-pollinated plants have light, dry pollen that easiliy becomes airborne. Canola varieties show a wide range of pollen characteristics, with pollen readily moved by insects or the wind (Timmons et al. 1995; Cresswell et al. 2004). Even in self-incompatible cultivars and hybrids that may require insect activity under regular field conditions, may be cross-pollinated sufficiently as the plants jostle against one another in the wind in high-density agricultural plantings. There are also legal and ethical concerns around the movement of genes in pollen from genetically modified (GM) crops to conventional crops (Timmons et al. 1995; Hayter & Cresswell 2006; Hoyle et al. 2007; Hoyle & Cresswell 2009). Cresswell et al. (2004) suggest that canola flower and pollen characteristics indicate zoophily, with any pollination by wind that may occur inefficient, and likely incidental.

Pollination Recommendations: The complexities and pollination requirements of canola modification through breeding and hybridization have yet to be fully understood. Insect activity appears to be a requirement in at least some self-incompatible canola, while in others the yields may not be significantly improved over that pollinated by wind activity, either by 'ordinary' anemophily, or by mechanical jostling of the flowers together in the field. Hybrid seed production, which makes use of spatially separated plants (alternating pollen donor rows and production rows), certainly requires insects to move pollen from the male to the female parent. The value of cross-pollination in product quality (oil concentration and composition in the seed) for various canola varieties also remains to be properly researched. The value of wild bees and flies in production and profitability of conventional, organic, and GM canola appears to both confirm the value of insects, and suggest that conservation measures for wild pollinators may be valuable for any grower (Morandin & Winston 2005, 2006; Turnock et al. 2006; Jauker & Wolters 2008). Some of these studies are experimental in nature (i.e. using pollinator enclosures), and care should be taken in translating results to commodity production. Abel et al. (2003) found that the blue orchard bee (Section 2.1.3) did an excellent job of canola pollination in experimental plots, but this organism is likely not a viable option for large acreages due to availability and the high labour involved in its husbandry.

Recommended deployment of honey bee hives varies considerably, with some researchers identifying large increases in yield that justify four or more colonies per hectare, and others identifying smaller improvements that warrant only one or two (Langridge & Goodman 1975; Westcott & Nelson 2001; Manning & Wallis 2005; Sabbahi et al. 2005; Oz et al. 2008), and still others suggesting that improvements in seed yield continue up to 15 colonies per hectare (Scott-Dupree et al. 1995). Some growers do not identify large enough benefits of adding managed pollinators when growing self-compatible canola varieties (Kevan 1988; Scott-Dupree et al. 1995; Westcott & Nelson 2001). These growers in particular may wish to consider conservation methods to encourage wild pollinators and their 'free' services (Morandin & Winston 2005, 2006; Turnock et al. 2006).

3.5.2 Sunflower (*Helianthus annuus*)

Mating & Breeding System: Sunflowers are a member of the aster family, and the large flower head that is visible is actually an inflorescence, or *composite flower*, made up of two kinds of tiny florets. The *disc florets* are located in the center of the composite flower, and the *ray florets* bear the outer ring of petal-like structures. The ray florets are sterile, and the disc florets have both male and female structures, the latter each with a single ovary that develops into a sunflower seed (Free 1993). A single flower head may have up to two thousand disc florets, each with the potential to develop into a seed. If there are multiple flower heads on the same plant, the number of disc florets per head will be much lower. The disc florets open in sequence, beginning at the periphery of the disc and moving inward. Each floret is first male, with the pollen-bearing anthers extending above the rim of the floret and dehiscing. Later, the style pushes through the shed pollen and the stigmatic lobes spread, opening receptive surfaces for pollination. If pollinator activity is adequate, they will have removed the pollen from each floret before the stigma opens, reducing the chances for self-pollination.

Pollination, Quality & Yield: If cross-pollination does not occur, the stigmatic lobes could curl downward to touch pollen shed by their own floret, should there be any remaining in the tube. Thus, self-pollination may occur as an emergency measure, although it is uncertain if this actually occurs (Free 1993). However, numerous pollinator exclusion and pollen supplementation experiments (i.e. Guynn & Jaycox 1973; Choi & Oh 1986; Dag et al. 2002; Nderitu et al. 2008; Oz et al. 2009) suggested that a set as low as 10-20% could be expected from self-pollination when pollinators were absent, compared to up to 90% set in flower heads accessible to pollinators. However, subsequent experiments showed that a high proportion of the self-pollination thus reported may have been due to the bags transferring pollen between florets on the same head (Free & Simpson 1964), and furthermore that florets were most readily self-pollinated when first open, and the chances declined with age (Radaeva 1954). It should be noted, however, that different cultivars have different levels of self-fertility, and many modern sunflowers are fully self-fertile. Cross-pollination may still be the preferred result, however, and appears to result in greater yield and higher quality both in terms of seed production and oil content. It is possible that fertility of self-pollen is highly reduced at high ambient temperatures, increasing the importance of prompt pollinators for seed set during hot weather (DeGrandi-Hoffman & Chambers 2006). Honey bees and bumble bees are effective managed pollinators of this crop in terms of number of seed, weight of seed, and proportional seed set (Aslan & Yavuksuz 2010).

Pollination Recommendations: While many species of bees will visit sunflowers, common practice is to place honey bee colonies (1-2.5 per hectare is considered sufficient; Kevan 1988; Free 1993) at the edge of the cultivated fields. It is generally held that adding honey bees is not necessary for self-fertile varieties (Kevan 1988; Scott-Dupree et al. 1995). Pollen appears to be the major attractant for honey bees to sunflower fields (Charriere et al. 2010). Certain sunflower varieties may have florets with tubes too deep for honey bees to effectively forage for nectar, a primary attractant, and this must be considered when planning pollination services. Many long-tongued wild bees and bumble bees have tongues of sufficient length to reach the nectar in the florets of these particularly deep varieties, and their contribution to pollination can be great. Furthermore, there is evidence that their activity can facilitate and improve honey bee pollination (DeGrandi-Hoffman & Watkins 2000; Greenleaf & Kremen 2006b). There are numerous species of solitary bees that are highly effective pollinators of sunflower, and methods for their encouragement and husbandry need further exploration. Bumble bees are also highly effective pollinators, with demonstrated yield improvements over honey bees, and further investigation of their management in this crop is warranted (Meynie & Bernard 1997; Aslan & Yavuksuz 2010). Male-sterile hybrid sunflower cultivars always require insect pollen vectors to fertilize female flowers (DeGrandi-Hoffman & Watkins 2000; DeGrandi-Hoffman & Chambers 2006).

3.5.3 Soybean (*Glycine max*)

Mating & Breeding System: Soybeans have small flowers with a typical legume morphology (see Section 1.2), and anthesis occurs and deposits the pollen within the keel before the flower opens. Some cultivars are entirely cleistogamous, meaning that the flower buds do not open and fertilization takes place with self-pollen entirely without external influence. To further complicate matters, other cultivars have flowers that only open when local environmental conditions are suitable (Erickson 1984). Natural pollen dispersal by insects or wind appears to be limited to very short distances (Ahrent & Caviness 1994; Ray et al. 2003; Yoshimura 2011), which is important both in soybean production, and in preventing the movement of genes between genetically modified (GM) and conventional soy crops (Yoshimura 2011).

Pollination, Quality & Yield: In the early history of soybean culture, it was thought to be both fully self-compatible and fully self-pollinating, and that the flowers were not visited by insects. However, most (75%) of soybean flowers abort, which could potentially be due to poor pollination or to limited resources. The former suggests that the more important role for honey bees may be in the facilitation of self-pollination, rather than cross-pollination (Delaplane & Mayer 2000), and most cross-pollination occurs between plants in close proximity (a few meters or less; May & Wilcox 1986; Ray et al. 2003). It is suspected that the benefits of cross- versus self-pollination is dependent on cultivar (Erickson 1975a; Erickson et al. 1978). Because some cultivars have flowers that only open when conditions are suitable, the bloom can vary within an area or even within a single large field (Erickson 1984). When conditions are suitable, however, soybeans produce some nectar, although tend to be a poor pollen resource (Erickson 1975a; Severson 1983). In addition to sometimes unclear research results, there is considerable anecdotal evidence that the presence of honey bees or wild bees can increase the yield of soybean, as observed within the vicinity of commercial hives in the case of the former, or near field margins with abundant wild flower visitors in the latter.

Pollination Recommendations: Further research into the value of adding pollinators, most likely honey bees since they appear to be among the most enthusiastic foragers when conditions are suitable, is required.

3.5.4 Peanut (*Arachis hypogaea*)

Mating & Breeding System: The peanut plant is a legume, with a floral structure typical of that family (see Section 1.2). It is unusual in that following fertilization, the flowers wither and turn downward, the ovary forms a 'peg' which pushes downward into the soil, and the seeds develop in pods buried in the soil. Generally, the anthers dehisce within the closed keel and self-fertilize the flower (Free 1993), although some authors have reported that a high percentage of peanut flowers were tripped by foraging bees (Leuck & Hammons 1965a). However, cross-pollination has been observed at very low levels. However, other studies have found no benefit to insect pollination of peanut (Blanche et al. 2006). Peanut can be a minor pollen source for bees, but the flowers do not produce nectar.

Pollination, Quality & Yield: Some yield improvements have been observed with both honey bees and wild flower visitors as the active agents (Leuck & Hammons 1965b; Girardeau & Leuck 1967). There is evidence that insect activity can improve number and weight of the resulting seeds, likely improving pollination by moving the pollen around and increasing the amount that contacts the stigma. Many different insects have been observed visiting peanut flowers (Free 1993). However, Blanche et al. (2006), working in Australia, found no improvements in yield associated with the activities of honey bees or wild bees. Girardeau & Leuck (1967) report modest increases of 6-11% in peanut yield associated with bee pollination.

Pollination Recommendations: Small bees, such as those in family Halictidae, seem to be best suited for manipulating peanut flowers and procuring resources, although large bees may expect to better trip the flowers. Honeybees will also visit peanut flowers to collect nectar, but do not seem to collect pollen or be as effective at moving it. Peanut growers wishing to experiment with the effects of insects on their crops should consider conservation measures that encourage small, ground-nesting bees, in addition to the possibility of adding honey bees to their fields during the bloom. However, the economic value of the increase in yield may not justify the cost of honey bee pollination, except possibly in large plantations or fields with very poor wild bee populations.

3.6 Greenhouse Crops

3.6.1 Tomatoes (*Lycopersicon esculentum*)

Mating & Breeding System: Tomato flowers grow in loose inflorescences, and hang with the reproductive organs pointing downward. They do not produce nectar, so a pollinator must be willing to forage for pollen only if they are to visit the flowers. The pollen is produced within the anthers, and must be shaken out through small pores (Buchmann 1983; Plowright & Laverty 1987). A visiting bee must collect pollen by hanging upside-down from the flower, grasping the stamens in its mandibles, and vibrating its body to agitate the flower. The pollen will then be shaken out through pores in the anther onto the underside of the foraging bee, where it can be brushed into the pollen baskets using the legs (Buchmann 1983; Plowright & Laverty 1987). The flowers are self-fertile, and the probability of self-pollination varies with different varieties, according to the relative timing of stigma receptivity, pollen availability, and the relative length of stigma and stamens.

Pollination, Quality & Yield: There is a relationship between the quantity of pollen delivered and the distribution of its delivery on the stigma, and with the marketability of the fruit in terms of size and shape. Tomatoes can be fully pollinated by self- or cross-pollen, and there is no evidence that cross-pollination improves quality. There is evidence that the quantity of pollen on the stigma is related to the rate of development, size and shape of the fruit, and/or the number of seeds produced (Kevan et al. 1991a; Dogterom et al. 1998; Morandin et al. 2001a).

Pollination Recommendations: Under field conditions, tomatoes can be self-pollinated through wind agitation shaking pollen loose from the poricidal anthers. This is not possible in the still air of the greenhouse however, and prior to the use of bumble bees in greenhouses human labourers had to "buzz" the flowers themselves using mechanical vibrators to release the pollen (Banda & Paxton 1991; Kevan et al. 1991a). The use of honey bees in greenhouse pollination is possible yet difficult because they do not favor still air and exhibit a tendency to attempt to leave and forage outside (Sabara & Winston 2003; Sabara et al. 2004). Furthermore, honeybees are not capable of buzz pollination. Commercial availability of bumblebees (*Bombus impatiens*), which are excellent buzz-pollinators, is now fully established in Ontario, especially for pollination of greenhouse tomatoes (Kevan et al. 1991a; Morandin et al. 2001a; Velthuis & van Doorn 2006).

Bumble bees have been demonstrated as equal or superior to electric pollination, in terms of both performance and cost (Banda & Paxton 1991; Pressman et al. 1999; Palma et al. 2008; Hogendoorn et al. 2010). Furthermore, reduction of pesticide use in modern greenhouses has made the use of bumble bees economically feasible. One commercially available bumble bee colony can be expected to effectively pollinate 1250 square meters of cherry tomatoes, or 2000-2500 square meters of regular tomatoes depending on the cultivar (see Section 8.0 for suppliers). This value may have to be adjusted in more densely planted operations, according to the recommendation of the bumble bee vendor. Since tomato flowers do not produce nectar, commercial producers include a source of sugar syrup inside of the colony container. Provision of additional sugar syrup by the grower may prolong colony life and further reduce pollination costs. The tendency of bees to leave through ventilation systems to forage for nectar outside the greenhouse can be diminished if the greenhouse material transmits rather that blocks ultraviolet (UV) light (Morandin et al. 2001b). Perception of UV light seems to increase their activity levels and reduce their desire to leave, possibly because the conditions are more representative of outdoor light.

3.6.2 Sweet and Hot Peppers (*Capsicum annuum*)

Mating & Breeding System: Cultivars of this plant include both sweet peppers and many varieties of hot peppers, all originating from Latin America. This discussion will be limited to sweet bell peppers, as production of hot peppers in Ontario rarely reaches a commercial scale beyond local markets. Much of the material presented, however, applies to hot pepper varieties, and a variety of insects will visit the flowers. It should be noted that many hot pepper growers are hobbyists who prefer controlled cross-breeding, and should therefore take steps to prevent open pollination. Although pepper flowers produce nectar in addition to pollen, they are self-fertile and most flowers can set fruit without cross-pollination. Like many members of the Solanaceae, peppers require physical agitation to release pollen from porous anthers, which can be accomplished by wind and/or buzz pollination by certain visiting insects (i.e. Raw 2000). The flowers have a large ovary surmounted by a style that is generally longer than the surrounding stamens. The stigma is generally receptive prior to the release of pollen (Free 1993).

Pollination, Quality & Yield: Evidence demonstrates that fruit set and yield is related to the bearing capability of the plant, either through breeding or resource availability. Several researchers in different parts of the world including Ontario have, however, found significant increases in fruit weight, mean fruit size, and mean seed number in greenhouse-grown hot peppers pollinated by domesticated bumble bees (Free 1993; Shipp et al. 1994; Dag & Kammer 2001; Ercan & Onus 2003; Kwon & Saeed 2003; Serrano & Guerra-Sanz 2006). Jarlan et al. (1997a,b) found similar improvements in fruit characteristics resulting from visitation by the drone fly *Eristalis tenax* (Syrphidae), but were unable to explain the mechanism by which the improvement occurred because the fly does not buzz-pollinate.

Pollination Recommendations: Wind is unavailable under greenhouse conditions, so insect activity is generally required to facilitate both self- and cross-pollination in pepper crops. The use of honey bees in greenhouses, while possible, is difficult because they do not like the still air, and tend to attempt to leave and forage outside (Sabara & Winston 2003; Sabara et al. 2004). Commercial availability of bumblebees (*Bombus impatiens*), which are excellent buzz-pollinators, is now fully established in Ontario, especially for pollination of greenhouse tomatoes (Kevan et al. 1991a; Morandin et al. 2001a; Velthuis & van Doorn 2006). A single hive of commerically available bumble bees can be expected to fully pollinate 3000 square meters of greenhouse sweet peppers.

3.7 Other Ontario Crops

3.7.1 American Ginseng (*Panax quinquefolius*)

Mating & Breeding System: Although the primary marketable product of ginseng is the root, ginseng seed is also a commodity marketable to growers. While individual flowers are protandrous (male function occurs before female function), each inflorescence will have functionally male and female flowers at any given time. Pollinator exclusion experiments have revealed that the plants are fully self-fertile, and sometimes even show enhanced fruit set when flowers are bagged (Carpenter & Cottam 1982; Lewis & Zenger 1983; Schluter & Punja 2000). It is possible that the activity of insects can facilitate movement of pollen within an inflorescence leading to occasional cross-pollination occurring, particularly in large commercial gardens. The major pollinators are wild bees, notably in the family Halictidae, and syrphid flies (Duke 1980; Carpenter & Cottam 1982; Lewis & Zenger 1983; Catling & Spicer 1995). Some growers will add honey bees to these large gardens at time of bloom.

Pollination, Quality & Yield: Bagging experiments have not demonstrated any reduced fruit set or seed production resulting from pollinator exclusion. However, it is possible that maintaining genetic diversity via cross-pollination in Ontario ginseng seed stocks is desirable due to the numerous disease pressures faced by the crop when grown in large gardens (Schluter & Punja 2002). In cross-pollination experiments with wild and cultivated ginseng Mooney & McGraw (2007) found that offspring from cross-pollinated plants had greater height, leaf area, and root biomass relative to offspring of self-pollinated plants. While this study was aimed at conservation of the endangered, possibly inbred wild populations rather than production of cultivated ginseng, the potential improvements in yield resulting from cross-pollination warrant further investigation.

Pollination Recommendations: Honey bees are sometimes placed in ginseng gardens to facilitate pollination in those operations that produce seed for their own use, or for market to other growers, at a recommended rate of 2.5 colonies per hectare. If insects are indeed required, or at least helpful, in facilitating pollination, then it is likely that in large operations wild pollinator populations will be insufficient for the needs of the crop. Pollinators used to foraging in open, sunlit conditions may be reluctant to visit plants grown under shade. Further research needs to be conducted into the quantitative benefits of cross-pollination to cultivated ginseng, if any, in terms of seed yield and offspring health, in addition to the effectiveness of available managed pollinators on the ginseng crop.

3.7.2 Buckwheat (*Fagopyrum esculentum*)

Mating & Breeding System: Buckwheat is an important staple in Eastern Europe, and most of the Canadian production occurs in Manitoba. Buckwheat has two different types of flowers, although both types have only one ovule each. One has short stamens with a long style (pin flowers), and the other has long stamens and a short style (thrum flowers). An individual plant typically has only one of the two types of flower. This condition, known as *distyly* or *heterostyly*, is a mechanism that promotes outcrossing (Bjorkman 1995a; Cawoy et al. 2009). The stamens are organized in an inner and outer ring, and an insect foraging for nectar must pass between them and get covered in pollen. Insects visiting the flowers acquire a pollen load on a part of their body that depends on the type of flower visited, and this is the body part most likely to touch the stigma of the opposite flower type during foraging (Free 1993). Due to the manner in which a visiting insect interacts with the sexual structures, the stigma of pin flowers will frequently be touched by pollen-bearing structures, giving it an advantage in female function. Similarly, pollen is more easily brushed onto the body of a visitor by the long stamens of the thrum flowers, leading to a thrum advantage in male function (Namai & Fujita 1995). It has been suggested that self-fertilization is possible but rare, with inhibition of pollen tube growth occurring if pollen from one type of flower lands on the stigma of a flower of the same type (pin or thrum), even if it is on a different plant (Elagin 1976; Free 1993).

Pollination, Quality & Yield: Under good growing conditions, buckwheat produces abundant nectar with a very high sugar content (Cawoy et al. 2009). Honey bees are enthusiastic workers of buckwheat flowers, with a highly desirable dark honey being produced by their efforts. In the absence of pollinators, seed yield is very low, only about 2-3% of the yield achieved when bees are present (Pausheva 1976; Racys & Montviliene 2005). Buckwheat flowers are attractive to many insects, and many can be important in improving yield whether or not managed pollinators have access to the flowers (Goodman et al. 2001; Cawoy et al. 2009; Taki et al. 2009).

Pollination Recommendations: Honey bees are the recommended pollinators of buckwheat, in large fields and in areas with deficiencies of wild pollinators, with optimal numbers of hives estimated between two and five per hectare (Kevan 1988; Free 1993; Bjorkman 1995b). Encouragement of other pollinators is recommended, however, as honey bees show a tendency to concentrate on thrum flowers, which have greater nectar production, and are not especially efficient at pollen transfer between the flower types (Bjorkman 1995b; Cawoy et al. 2006, 2009). Elagin (1976) found that the maximum yields were attained with three hives per hectare, and Bjorkman (1995b) suggests that adding more bees above a certain level will not improve pollination or yield. While buckwheat benefits from multiple insect visits, pollen tube growth and fertilization tends to occur very quickly (5-20 minutes, depending on flower type; Cawoy et al. 2009). Honey bees work the flowers very quickly, spending only a few seconds at each, and therefore likely saturate the field at these hive deployment levels (Bjorkman 1995b; Cawoy et al. 2009). Since much of this original research was performed in Europe and Russia, there is a need to investigate questions of productivity, pollen and nectar resources, and pollination in Ontario, particularly with modern varieties which may have differing degrees of self-compatibility and nectar production. Buckwheat could become an important plant, as a crop, a source of nutrition for honey bees and wild pollinators of all types servicing other crops, and a high quality honey plant.

3.7.3 Tree Nuts

Many nuts are typically grown under warmer conditions than are found in Ontario, but there are several types of nuts that are native to the province that show potential for local consumption or commercial development (beaked hazelnut, black walnut), and others grown commercially in other parts of the world that have been imported. Many nuts require long hot growing seasons, and because many are growing near the northern limit of hardiness, they can be a risky crop. Most are wind-pollinated and self-fruitful, although there are exceptions, and wild populations of at least some species appear to have mechanisms in place to encourage cross-fertilization (McCarthy & Quinn 1990), and produce higher quality nuts when cross-pollinated.

American Chestnut (*Castanea dentata*) The chestnut was once an important tree in eastern deciduous forests, with the northern edge of its distribution in southern Ontario. Since the introduction of the chestnut blight in 1904, the species has declined precipitously in the wild, and few mature trees remain in Ontario forests (COSEWIC 2004). Chestnut is self-compatible, but generally requires cross-pollination because the male and female flowers do not bloom simultaneously on an individual tree. The flowers are in the form of catkins, and a variety of pollinators collect both nectar and pollen from the flowers. Unlike most other nut trees, the American chestnut is pollinated by insects. Wild trees generally cannot reproduce due to the isolation of individual trees (COSEWIC 2004), and artificial propagation is necessary to save the species.

Insect pollination of the related Caucasian chestnut tree *Castanea sativa* by honey bees can improve total nut yield (Sokolov & Chernyshov 1980; De Oliveria et al. 2001b). It was experimentally recorded in the former USSR that the presence of honey bees improved yield in chestnut groves (*C. sativa*), and 1.5 colonies per hectare was recommended (Sokolov & Chernyshov 1980). The self-sterility of chestnut requires that pollenizers of a different variety be included, at a rate of one-tenth to one-half of the production trees. The pollenizers and production cultivars can be planted in different rows to simplify the harvest, particularly if the product is noticeably different (Vossen 2000).

Almond (*Prunus dulcis*) Almond deserves special mention, for although not commercially cultivated to any great extent in Ontario due to our climate, it is one of the most valuable crops and one of the largest pollination demands of managed honeybees in the world, most notably in California (DeGrandi-Hoffman 2001). It is a member of the same genus as stone fruits (cherry, plum, peach, apricot, nectarine), but differs in that the stone (nut) is the primary crop. The flowers are self-incompatible, and require cross-pollination, with pollen from an appropriate pollenizer cultivar, by insects in order to set fruit and produce seeds. There has been a trend toward the development and use of self-compatible almond, although the effect on yield, size, and flavour quality of the resulting produce requires further evaluation, as it may be negatively affected by self- versus cross-pollen (Ortega et al. 2006; Kodad & Company 2008; but see Martinez-Garcia et al. 2011).

The transfer of pollen from a compatible pollenizer to the flower of the producing cultivar is essential for fruit set to occur, and insects are required to carry the pollen. Research has shown that the compatible trees must not be more than a few meters apart for optimal fruit set, as honey bees have a tendency to focus a foraging trip on a single tree or cultivar (Jackson 1996). However, it has also been found that most (90%) of honey bees in an almond orchard do carry cross-pollen on their bodies (DeGrandi-Hoffman et al. 1992), in the case of honey bees (and possibly other social bees, but not solitary insect visitors) much of this pollen acquisition may occur via transfer between foragers within the hive.

Early pollination is essential in Ontario, if the tree is to have a chance to produce mature fruit. Because each flower contains only one pair of ovules, asymmetry of poorly pollinated fruit is less of a problem than in the pome fruits, although poorly pollinated blossoms may drop. Almond growing in Ontario is generally restricted to hobbyists and landscaping use, as the climate is too harsh and unpredictable for commercial production. The presence of toxic compounds such as amygdalin in almond nectar and pollen can be problematic for pollinators if consumed in large doses, and is a particular problem for honey bees pollinating large almond monocultures (Kevan & Ebert 2005). Bumble bees (see Section 2.1.2) and blue orchard bees (see Section 2.1.3) have demonstrated potential for pollinating almond (Free 1993), and wild bees and possibly flies are may also be valuable. although further research is necessary into their effectiveness for this particular crop.

Walnut, Butternut, Heartnut (*Juglans* spp.) Cultivated members of this group in Ontario includes the native black walnut (*Juglans nigra*) and butternut (*J. cinerea*), and the exotic Japanese walnut, also known as the heartnut (*J. ailantifolia*). The cultivated walnut familiar to most consumers is the Carpathian walnut (*J. regia*), and are comparable to apple in hardiness for Ontario. There is also a hybrid of the butternut and the heartnut, which is known as the buartnut. Members of genus *Juglans* are monoecious and wind-pollinated, with the male and female reproductive structures in separate flowers on each tree. Male flowers are found on long, pendulous catkins, while female flowers are small and inconspicuous, borne near the tips of the growing branches. Individual trees, while self-compatible, typically release pollen before or after the female flowers are receptive (depending on cultivar), thereby precluding self-fertilization. Thus, other trees of an appropriate cultivar are necessary in order to ensure that pollen is available to the production trees during female receptivity (Polito et al. 2003). Pollination by a suitable cultivar is generally required to set a nut crop. Even those species and cultivars that are self-fruitful, such as the heartnut, will produce a larger crop if cross-pollinated.

Hickory nut (*Carya* spp.) This genus is also a member of the walnut family, and has similar reproductive biology. It includes a number of valuable nut crops such as pecan, which are not commercially grown in Ontario due to our harsh climate. Shagbark hickory (*Carya ovata*), shellbark hickory (*C. laciniosa*), northern pecan (*C. illinoinensis*) are just several varieties. Also available are "hican" trees, which are a hybrid between shellbark hickory and pecan. Pecans in particular are poorly suited to the Ontario climate, although there are some naturally occurring genetic lines that have been found growing in midwestern states as far north as southern Wisconsin. These trees were likely planted by First Nations, and those that managed to survive and produce fruit resulted in small, localized populations. All trees in this genus are self-fruitful, but the quality of the product is generally believed to benefit from planting of mixed cultivars (as much as possible considering the climate) (Wood 1997). The trees can be expected to abort a high proportion of pistillate flowers whether or not they have been pollinated, but this is a response to resource availability rather than pollination deficiencies (McCarthy & Quinn 1989).

Hazelnut / Filbert (*Corylus* spp.) There are several cultivated species of hazelnut, also known as filbert, and most are European in origin. The most commonly cultivated species is *Corylus avellana*, the European hazel. There are several species native to the New World that produce edible nuts, including American filbert (*C. americana*) and beaked hazelnut (*C. cornuta*). Hazelnuts bear flowers in the form of catkins, with male catkins and less conspicuous female flowers occurring separately. Both sexes are found on the same tree (*monoecy*) in most cases, although a few single-sex plants may occur. Beaked hazelnut, at least, is self-incompatible. For all species, growers typically plant two varieties together to facilitate pollination and nut set. European hazelnuts are wind-pollinated, with cross-pollination preferred despite some level of self-compatibility in this species. Although it produces smaller nuts, the native species are the preferred choice in most parts of Ontario, as the cultivated European hazel is not as hardy.

4.0 Using Pollinators Effectively

4.1 Protection from weather

Managed pollinators must variously be protected from heat, cold, wind, or moisture, depending on the time of year, terrain, and prevailing conditions in the field. When placed in the field for pollination, it is best to place the hive or domicile such that openings face to the south or southeast, to facilitate warming in the morning and encourage bee activity (Kevan 1988; Scott-Dupree et al. 1995; Delaplane & Mayer 2000; Slingerland et al. 2002a). This is particularly important for early season crops, such as orchard fruit, where loss of pollination time due to inclement weather is a particular concern. Shelter from strong wind is also important, but the hive or domicile should not be placed in a way that encourages dampness, impedes circulation of air around or within the hive, or impedes the entrance and exit of insects, for instance by overgrown vegetation.

4.2 Provision of water

Like any animals, managed and wild pollinators require water to survive, and the effort required to forage for water can significantly detract from pollination activities, particularly in dry or hot weather. In addition to drinking the water individually, bees also use the water to cool the hive in hot weather using evaporative cooling, and thus maintain an optimal temperature for the brood. On a very hot day, fulfilling the water needs of a hive can fully occupy several hundred workers in collection and delivery, which is a significant proportion of the foragers that would otherwise be engaged in pollination. Foragers gauge the need for water in the hive by how eagerly the water they deliver is accepted by the bees working inside. Other uses of water in the hive include rehydration of crystallized honey, in order that it may be consumed by the bees as well as production of gland secretions by nurse bees that are utilized to feed larvae.

The energetic cost of foraging for water can be minimized for managed bees simply by placing containers of fresh water in the vicinity of the hives or domiciles if natural sources of surface water are not available nearby. Water sources (and bees) should be kept away from areas that may be affected by drifting pesticides. Insects will frequently become trapped and drown in simple dishes or buckets, so containers should have floating or leaning objects in the water that allows the insects to climb in and out, and access the water from a surface to which they can comfortably cling. Some floating wood chips or sticks of wood leaning against the side of the container will serve well. More permanent containers or small ponds can make use of floating live plants such as water lily as drinking platforms. Other options include pet or livestock watering devices, or even a simple puddle maintained by a dripping faucet. When designing farms with wild pollinator conservation in mind, the presence of water near the nesting habitat can significantly increase survivorship and pollination activities. Some pollinators, such as mason bees (including managed *Osmia lignaria*, the blue orchard bee) use mud in their nest construction, so require a source of suitable construction material nearby, best found near the edge of a pond or stream. The shorter the distance that the bees have to travel to find these essential resources, the greater the amount of time that they can spend pollinating the crops and provisioning their nests.

4.3 Habitat and off-bloom food resources for pollinators

When considering how to manage non-crop plants on the farm, it is important to remember that pollinators forage on plants to produce the next generation of pollinators. The life cycle of honeybees lasts year-round, bumble bees for a single growing season, and even solitary bees have life cycles that are longer than the bloom period of most crops in Ontario. Management of pollinators requires that their nutritional needs be considered for the entire season, not only the period during which they are foraging on the crop. In the past, the tendency has been to herbicide or mow non-crop plants both from within the cultivated area and at its margins. While it is true that these plants can act as weeds and harm crops through competition for resources, many have flowers that are insect-pollinated, and thus produce resources to attract pollinators. A varied diet and broad nutrition is good for all pollinators, in order that a full complement of nutrients can be obtained for successful growth and reproduction. In addition to the need for a water source, wild pollinators require habitat that will support their larvae, and also habitat that will provide food resources before and after the crop is in bloom. These requirements vary with species, but are critically important as they not only support the pollination activities of the insects now, but ensure the production of the next generation to pollinate future crops. Wild pollinators do not forage as far as honey bees, so crops more than about 75m from suitable habitat are unlikely to be visited by these insects.

Wild pollinators visit flowers to satisfy their own energetic requirements by consuming nectar, and in the case of bees to collect pollen to provision their larvae. Many of Ontario's wild solitary bees are ground-nesting species, requiring dry sandy soil with structure and low-density vegetation. These nests can occur in field margins and in the cultivated area itself, and are easily destroyed by deep tillage. Others nest in cavities between stones, in wood, hollow twigs or stems, and similar protected spaces. Bumble bees find larger natural cavities for their colonies, such as abandoned rodent burrows and other sheltered spaces. The habitat requirements of pollinating flies are even more varied, although the larvae of most do not consume floral resources. Some larvae, notably those of syrphid flies, can be predatory on damaging insects such as aphids.

There are numerous agricultural practices that can be detrimental to wild pollinator populations. Conservation of alternative forage and conservation of nesting habitat go hand-in-hand, and may be as simple as allowing field edges, hedgerows, and low productivity areas on the farm (for example, areas of perpetually dry or wet soils, corners difficult to access with machinery) to provide forage and safe nesting sites by reducing human interventions such as tillage, mowing, or spraying. Large fields may also need patches ("bee pasture"; Decourtye et al. 2010; Zurbuchen et al. 2010) permanently given over to minimally disturbed revegetation, but these can be integrated with other efforts, such as drainage and erosion control, or windbreak improvement. Growers may realize an economic benefit by "retiring" less productive or difficult land (i.e. former wetlands) to conservation roles, providing forage and habitat for pollinators that can then benefit their crop. Competition from other plants for pollination services during the bloom can negatively affect crop success, but availability of forage for the pollinators outside of bloom time is good for both managed and wild pollinators (i.e. Carreck & Williams 2002; Pontin et al. 2006; Sheffield et al. 2008b). Farm conservation organizations such as ALUS have been established to assist growers with this process, and may even provide financial assistance. Increasing the area of this marginal land dedicated to conservation purposes on the farm will increase the population of wild pollinators, and increase the pollination service that they provide to the crop. This, in turn, can lead to increased profitability, as costs associated with cropping marginal land are reduced (Kremen et al. 2004; Morandin & Winston 2006; Morandin et al. 2007). This land can be incorporated into other farm conservation projects, including flood control and water management, erosion control, and provide food and habitat for other wildlife.

4.4 Colony Strength and Recommended Standards

The colony strength of honey bees is a major consideration when deciding to use them for pollination services (Scott-Dupree et al. 1995; Frazier 1999; Sagili & Burgett 2011). A beekeeper may provide legal documentation of the strength of the supplied colonies, certified by an apicultural consultant qualified to do so. An accurate but labour-intensive method is the counting of "frames", estimating the quantity of brood and number of adult bees available for pollination as a representation of colony health. The number of bees on the frames may be lower if it is a warm sunny day and a significant proportion of foragers are outside the hive. A strong colony will produce plenty of foraging workers to visit the crop. If the weather conditions are suitable for foraging (i.e. 15C or higher, low wind speed), strength can be evaluated by counting the number of bees active at the hive entrance. The Canadian Honey Council (see Section 8.0) recommends that there should be a minimum of 60 bees per minute leaving the hive under these conditions. A significant number of returning foragers (about one-third) carrying pollen signifies that an adequate number of bees are foraging for pollen and therefore pollinating, and also that the colony is actively rearing brood. Plenty of brood stimulate the foragers to collect pollen, which will improve pollination of the crop. A hive used for pollination should have a minimum of two Langstroth hive bodies, to allow expansion of the colony and discourage swarming resulting from overcrowding. Overcrowded bees will reduce their brood production and foraging activity, and therefore their effectiveness as crop pollinators (Scott-Dupree et al. 1995).

If the weather is less amenable to foraging, strength is traditionally estimated by counting "frames". Colonies suitable for pollination in Ontario will contain a healthy laying queen, at least 20000 cm^2 of comb with 6500 cm^2 filled with live brood, and enough adult bees to cover 8-10 standard frames (Kevan 1988; Scott-Dupree et al. 1995). For crops that bloom early in the season (i.e. orchard fruit), a suitable colony may have 6-8 frames of adult bees and 4000 cm^2 of live brood, as there has been little time for strength to build after the winter. Grade B colonies, which command a reduced pollination fee, may have up to 25% fewer adult bees and 25% less brood coverage. Furthermore, the colonies should be free of American foulbrood, and have minimal presence of other diseases, such as European foulbrood (Kevan 1988). A similar but quicker method of estimating strength evaluates the size of the cluster only (frames covered with adult bees), and bees do not have to be shaken off the frames in order for the brood to be evaluated (Nasr et al. 1990).

4.5 Use of pollen dispensers and inserts

Pollen dispensers are devices that fit on the front of the home of a managed pollinator, such as a honey bee hive or bumble bee domicile, into which pollen of the appropriate species may be placed (Townsend et al. 1958; Dicklow et al. 1986). The dispenser is designed so that the foragers must walk through the pollen as they move through the exit. The bees get additional pollen on their bodies, and thus deliver more pollen to the crop while foraging. Weather unfavourable to honey bees is a consideration for choosing to use pollen inserts, as they may reduce the total time that the bees must work the crop and therefore the extra pollen carried to the flowers is a benefit. This is a consideration in early blooming crops, particularly orchards. In some cases significant yield improvements have been observed (Townsend et al. 1958; Jaycox & Owen 1965; Dag et al. 2000), while in other cases the practice was largely ineffective (i.e. self-incompatible apricot; Vaissiere et al. 2006). In the latter case, the bees were observed collecting the pollen from the dispensers and packing it into their corbiculae, and most of it was never carried to the crop.

Probably the greatest difficulty in using pollen dispensers is acquisition and care of the pollen itself. No substitute for real pollen has been invented, so the only option is the expensive collection of pollen from flowers by either bees (using pollen traps on the hives) or human labourers, which must be an appropriate pollenizer cultivar for the target crop, if applicable. Bee pollen requires special treatment to "unpack" (release from its pelleted form) and make useable again as free, viable pollen, a process that involves washing in a series of solutions, followed by drying with cold air (Free 1993). Pollen thus treated can be frozen, and used up to two years later, although once thawed it must be used immediately. Pollen collected dry directly from the flowers does not require such processing, although it may clump if not promptly used. If treated properly, pollen can be frozen and stored for up to two years and still show acceptable germination rates. Its use must be carefully planned, however, as it only retains germinability for a period of hours once unfrozen and placed in the dispenser (Dicklow et al. 1986). Devices similar to dispensers are being developed that make use of colonial managed pollinators to deliver biocontrol agents for plant diseases or insect pests (going out of the hive) or medicaments for various bee health issues (going into the hive). In addition to having good flying weather when placing the bees in the crop, when using pollen inserts it is very important that the bloom be well underway, which will encourage the bees to visit those nearby fruit blossoms. If few flowers on the crop are open when the pollen inserts are deployed, the bees may not stay on the crop and forage elsewhere, and the supplied pollen will be wasted.

4.6 Chemical manipulation of pollinator behaviour

There are several chemicals available on the market that exploit the chemical agents that honey bees use to communicate information and regulate conditions and resources within their colonies. Some operate by attracting the bees to the crop, hypothetically improving pollination by increasing bee presence (and thus foraging), and reducing competition from more attractive blooms that may be present nearby (Delaplane & Mayer 2000). This can be particularly important in crops that are not particularly attractive to honey bees. Others, such as brood pheromone, manipulate behaviour within the hive to encourage pollen foraging in general. If the bees are collecting more pollen on the crop, they are moving more pollen around and theoretically increasing cross-pollination. Additional research may lead to more effective use on specific crops (Currie et al. 1992a,b; Schultheis et al. 1994; Ambrose et al. 1995; Delaplane & Mayer 2000; Ellis & Delaplane 2009).

Queen Mandibular Pheromone (QMP) is a group of (at least) five active compounds produced by queen honey bees, from glands near their mouth, that plays numerous roles in queen control of the colony and colony cohesion. Products containing synthetic QMP, such as FruitBoost™, are used to increase foraging activity of worker bees when sprayed on a crop, and elevated levels of QMP are also correlated with increased pollen foraging activity, which can translate to higher rates of flower visitation and thus greater pollination (Higo et al. 1992, 1995). Individually, the compounds do not elicit a response, but must be present together (Trhlin & Rajchard 2011). Synthetic QMP can also be used within the hive to simulate the presence of the queen in a colony that has become queenless (PseudoQueen™), normalizing the activity of the workers until the queen can be replaced by the beekeeper. It has been suggested that synthetic QMP lacks one or more components present in bee-derived QMP, and therefore may not be as effective as claimed (Maisonnasse et al. 2010; Trhlin & Rajchard 2011). Ellis & Delaplane (2009) found that application of FruitBoost™ was unable to improve pollination when more attractive sunflowers were blooming nearby. In tree fruits, experiments at various QMP concentrations demonstrated no effect on yield or fruit quality in apple or sweet cherry orchards, but that a significant economic return could be achieved in pear, which is normally unattractive to pollinators due to low-quality nectar (Currie et al. 1992a; Naumann et al. 1994). Similarly, spraying cranberry and blueberry crops increased yields, although it was possible to concentrate the QMP too strongly, which was deterrent to visiting honey bees (Currie et al. 1992b).

Brood pheromone is produced in the salivary glands of larval honey bees, and its presence communicates to the worker bees that larvae are present and require pollen for nutrition (Pankiw et al. 1998; Trhlin & Rajchard 2011). It is suggested that the use of commercially produced, stabilized brood pheromone (SuperBoost™) inside a colony simulates the presence of more brood that require more pollen, which therefore encourages the foragers to collect more pollen, visiting more flowers and effecting more pollination on the crop. Experimental application of brood pheromone to honey bee colonies placed on blooming cucurbits improved both the proportion of pollen foragers and the size of the pollen loads that they carried from the target crop (Pankiw 2004). The product may also have benefits for the bee colony, including more brood, greater honey production, potential for colony splitting, and improved overwintering success. From a pollination standpoint, the use of brood pheromone in this manner results in more pollen and nectar foragers, higher flower visitation rates, greater pollen loads and more pollen brought back to the hive, and more adult bees (Pankiw & Rubink 2002; Pankiw 2004, 2007).

The commercially available attractant BeeScent™ is a commercial blend of pheromones that is believed to attract bees when sprayed onto a blooming crop. It includes a synthetic Nasonov pheromone. Nasonov pheromone is a cocktail of volatile chemicals secreted by bees as a means of attraction and cohesion among nestmates, has been demonstrated to cause bees to congregate in an area, and may be used by beekeepers to attract and capture swarms. It is also used by bees in the field to recruit foragers to high quality sources of food and water, both in the field and during dance communication (Wells et al. 1993; Trhlin & Rajchard 2011). Mayer et al. (1989b) found increases of 50-100% in bee activity in sprayed crops, although there is doubt whether BeeScent™ is any more attractive that other odours detectable by the bees, such as cinnamon oil, or improves productivity or profitability of the crops to which it is applied (Wells et al. 1993; Ambrose et al. 1995). BeeLine™ differs from the other products discussed here in that it is not a pheromone, but rather a wettable powder food supplement containing sugars, fats, proteins, and other nutrients, that is intended to attract bees and other pollinators to the crop and stimulate their desire to feed. Some trials have had disappointing results in both the ability of BeeLine™ to attract bees, and to improve seed sets or yields (Rapp et al. 1984). Even if pollination is not improved, it is likely to improve the health of the visiting insects.

5.0 Pesticides and Pollinators

5.1 Preventing pollinator poisoning

Pesticide poisoning is a pervasive problem in the agricultural landscape, and the lethal and sublethal ramifications for managed and wild pollinators are difficult to predict and quantify (Johansen 1977; Kevan & Rathwell 1988; Thompson 2003; Mineau et al. 2008; Scott-Dupree et al. 2009; Barmaz et al. 2010; Brittain et al. 2010; Tuell & Isaacs 2010). *Communication*, between growers, beekeepers, neighbours, and agriculture professionals, is the most important tool in protecting bees from accidental pesticide poisoning. However, growers and pesticide applicators should be aware of how difficult, time-consuming, disruptive to the bees, and generally unsatisfactory wrapping or moving bees is for the beekeeper. Most knowledge of pollinator poisoning by pesticides relates to managed pollinators such as honey bees and bumble bees, and most toxicological data are derived from laboratory studies. Although toxicity levels of a given pesticide will vary considerably among pollinators, the information given in this section also applies to wild pollinators, who often go unnoticed and which cannot be moved or protected prior to spraying (Thompson & Hunt 1999; Thompson 2001). During the process of foraging, bee colonies act to concentrate pollutants, including pesticides, from the surrounding landscape into the wax, stored pollen and nectar, and the bodies of the adults and brood (Conti & Botre 2001; Mullin et al. 2010). There is a pressing need to expand the pesticide registration process to include the effects on pollinators in the field, sublethal effects, and effects on wild pollinators (Abbott et al. 2008; Mineau et al. 2008; Scott-Dupree et al. 2009; Barmaz et al. 2010; Fischer & Moriarty 2011).

Because they are specifically designed to kill insects, insecticide exposure is obviously of paramount concern, but pollinators can also have negative responses to exposure to some fungicides and herbicides (Gregorc & Ellis 2011). Pollinators may be exposed to pesticides both orally and through external contact, by walking or flying in sprayed areas, or consuming food or water that has been contaminated. In the case of honey bees, brood, younger workers, and the queen may be exposed when foragers return to the hive with contaminated food and water. Fungicide products containing the active ingredients captan and ipridione can damage the brood (Riedl et al. 2006). There is some evidence that exposure to certain fungicides can amplify the toxicity of certain insecticides, but further research is required to confirm that these observations translate to effects in the field (Schmuck et al. 2003; Iwasa et al. 2004). A recent study also points to a synergistic effect between certain pesticides and antibiotics used to treat diseases of the honey bees themselves (Hawthorne & Dively 2011). Translation of these studies to field exposures of pollinators is difficult, as exposure to other stressors (environmental conditions, disease, nutrition) can alter the effects of exposure. Even less is known about sublethal and chronic health effects, including those that may affect such things as foraging, spatial skills, learning, and cognition, and which may impair the pollinators' performance in the field (Thompson 2003; Mommaerts et al. 2010; Skerl et al. 2010; Fischer & Moriarty 2011; Wu et al. 2011).

The need to spray is reduced on many transgenic crops, which may be a benefit to pollinators as current research has found that these crops are relatively benign to adults and larvae of managed bees (Malone & Pham-Delegue 2001; Malone et al. 2007; Rose et al. 2007; Duan et al. 2008). Since the toxins produced by transgenic plants are proteins, if pollinators were to come in contact with the toxins it would likely occur in the pollen, the major protein source for bees and some other pollinators (proteins are generally not expressed in other resources such as nectar and resin; Malone & Pham-Delegue 2001). Testing of lethal, and especially sublethal effects, is necessary to assess long-term health of bee colonies that collect and store pollen from genetically modified crops (Sabugosa-Madeira et al. 2007; Benbrook 2008). If toxins of any provenance are found in the pollen or brood comb, there may be effects on larval health and reproductive success of the hive, even if lethal effects on adult bees are not evident (Kevan et al. 1984; Sabugosa-Madeira et al. 2007; Benbrook 2008; Skerl et al. 2010; Fischer & Moriarty 2011; Wu et al. 2011). In addition to toxic effects on the bees themselves, herbicides can harm a colony by destroying alternative food sources, insect growth regulators can be particularly damaging to brood, and even nectar and pollen stored in the hive can cause health problems later if it is contaminated.

Routes of exposure in the field are diverse, and can result from accidents or equipment malfunction, human error, misuse, or illegal use of pesticides, drifting of pesticide aerosols into an apiary or onto blooms being visited by foraging insects, and so forth. Dusts and wettable powder formulations often show greater toxicity that do liquids or granulated forms. There are also emerging problems related to seed treatments containing insecticides, as dust blowing from fields during planting (Greatti et al. 2006; Alix & Lewis 2010; Tremolada et al. 2010), or oral uptake of residues that may be found in nectar, pollen and guttation droplets, leading to lethal or sublethal effects on bees (Benbrook 2008; Girolami et al. 2009; Alix & Lewis 2010; Fischer & Moriarty 2011; but see Nguyen et al. 2009). Spray equipment must be in proper working order, with the appropriate nozzle chosen for the desired spray, according to label instructions. Drift control is another critical consideration, and ground application should be used instead of aerial application whenever possible. Serious honey bee kills can result if insecticides are applied to a crop containing blooming weeds, even if the crop itself is not in bloom. Bees can collect contaminated pollen and nectar from a field and carry it back to the hive, potentially harming the queen and brood (Riedl et al. 2006; Gregorc & Ellis 2011). Quality scouting and economic threshold decision tools should be used when possible to minimize pesticide use wherever possible. This makes good business sense as well as good ecological sense.

Pollination contractors are often acutely aware of these dangers to their bees, and may refuse to place their bees near a field that may be sprayed while their bees are foraging in it, or where spray may drift onto the hives, onto blooming plants in the field margins, or onto the crops which they were hired to pollinate. For example, some beekeepers will not rent bees for use on fields close to sweet corn if the corn will be in bloom during the contracted period. If spraying must occur near honey bees, the best option is to remove the hives from the area entirely. Failing that, covering the hives with damp burlap will afford the bees some protection, and spraying during the hours of darkness is also desirable. Bees that are covered must be left some room and provided with an accessible source of fresh water (see Section 4.2) under the cover to allow them to cool the hive during the confinement (Scott-Dupree et al. 1995). Feeding the bees with sugar syrup may help keep the nectar foragers inside the hive during the dangerous period also. Solitary bee domiciles (alfalfa leafcutter bees, orchard bees) may be moved out of the area at night when the females are resting in the tubes to afford a measure of protection. They should be stored at a cool temperature until the hazard has passed and they can be returned to the field (Riedl et al. 2006). In greenhouse crops, foliar application of insecticide can harm managed bumble bee pollinators, but at least in one case (using thiamethoxam) switching to application via the irrigation system eliminated negative effects on the pollinators (Sechser & Freuler 2003). This method has not been tested on high-value outdoor crops receiving drip irrigation, but may hold some promise.

5.2 Detecting pollinator poisoning

The most obvious sign that pollinators have been poisoned are lethal effects, where piles of dead and dying bees accumulate near hives, or there is a sudden decline in the adult population of a hive as foragers leave and do not return. Death of approximately 100 adult bees per day is considered a typical rate of loss for a healthy colony, but if a beekeeper observes more than 200-400 lost there may be cause for concern (Johansen 1977). Other symptoms can include the presence of dead brood in the hive, reduced level of brood care (i.e. fewer nurse bees), and a decline in brood-related activities such as depleted food stores. Surviving bees will work to remove dead adult bees or brood and deposit them outside the hive, and these can serve as another indication of a problem. Considerably less research has been conducted on sublethal symptoms and toxicology, which can harm the ability of bees to perform their duties inside and outside the hive, even if they do recover from the pesticide intoxication (Decourtye et al. 2004). There are many possible sublethal effects on honey bees that can occur due to impaired movement, reduced navigation ability, reduced learning ability, and so forth. Symptoms of such problems include unusual aggressiveness displayed by the bees, including confusion and fighting at the hive entrance as recognition of nestmates is impaired. Poisoned adult bees may appear sluggish or paralyzed, unable to fly or crawl properly and resting on nearby objects or lying on the ground. Some insecticides (organophosphates) can cause regurgitation of collected nectar from the honey stomach ("wet bees"; Johansen 1984; Scott-Dupree et al. 1995; Riedl et al. 2006). It should be noted that many of these symptoms can have causes other than pesticide poisoning, such as plants with toxic nectar and certain bee paralysis viral diseases, and therefore a toxicological analysis is imperative, particularly if recompense for damages may be sought (Riedl et al. 2006). Loss of managed solitary bees is usually not as obvious, although females will be conspicuously absent from the domicile area and males may appear confused by their absence (Riedl et al. 2006).

5.3 Treatment of Poisoned Honey Bee Hives

There is, of course, very little that can be done for individual bees that have received a lethal dose of a chemical. Little is known about sublethal effects of pesticides on pollinators in general, but it is likely that the ability of bees to perform their duties inside and outside the hive may be compromised, even if they do recover from the pesticide intoxication. However, the hive can recover if the queen is intact, and resources (supplementary sugar syrup, plus pollen or pollen substitute) can be provided to stimulate rearing of replacement brood (Scott-Dupree et al. 1995). If a pesticide application results in a bee kill, both applicator and farmer should be notified immediately to terminate spraying. This will stop further damage and allow hives to be moved or protected.

5.4 Arranging for Toxicological Analysis

If a poisoning incident is suspected, beekeepers and growers will be able to arrange for chemical analysis of bees or hive products to detect pesticide residues. Certain commercial laboratories will be willing to perform analyses, but often for a considerable fee. It is important to collect a sample of dead or sickened bees as quickly as possible, and preserve as many as possible in a glass jar in a home freezer until analysis can occur. The bees should be collected in front of a third-party witness. Record the date, actions taken, pesticides used, and weather conditions during and after the suspected pesticide application occurred (Johansen 1984).

In Ontario, bees are analyzed for pesticides through OMAFRA at Laboratory Services Division, University of Guelph, 95 Stone Road West, Guelph, ON, N1H 8J7. Arrangements should be made through Linda Lissemore at 519-767-6218 (llissemo@lsd.uoguelph.ca), Mary-Anne Denomme at 519-767-6208 (mdenomme@lsd.uoguelph.ca) or Perry Martos at 519-767-6209 (pmartos@lsd.uoguelph.ca). A weblink to further information and costs can be found in Section 8.0.

The suspected poisoning incident should also be reported to the Office of the Provincial Apiarist (1-888-466-2372 ext. 63595; paul.kozak@ontario.ca). If possible, consult the laboratory that will be performing the analysis for more specific instructions, including minimum sample size and storage protocols. Pesticides may accumulate in hive materials (stored pollen, wax, etc) or products (honey), but any positive result will be very difficult to link with a particular suspected incident.

5.5 List and Relative Toxicity of Pesticides for Ontario Crops

Pesticide use in the presence of any pollinators should be minimized wherever possible, and no pesticide should be used on a blooming crop or near an apiary without giving beekeepers adequate advance warning. The following list of pesticides taken from Fell (2011), will serve as a guide to pesticide toxicity to honey bees, which is typically the main (or only) pollinator subjected to toxicological testing, and only for lethal effects. Extensive details are found in Riedl et al. (2006). See also current information table from OMAFRA website, and older information in Kevan & Rathwell (1988).

5.6 Chemical Classes

Many insecticides in the chemical classes listed below can cause confusion in honey bees if exposed, which takes the form of aggression between guard bees and returning foragers. This can be caused by cognitive impairment, or by the foragers' pollen loads themselves if they are contaminated by pesticides (Riedl et al. 2006). Foraging adult bees affected in the field may not be able to return and simply disappear from the hive, and the only symptom will be an elevated loss rate of adult bees. However, if applied pesticides are returned to the hive by foragers in pollen or nectar loads, or drift into the apiaries themselves or are applied to crops when hives are present, symptoms may be observed directly.

Organophosphates

There are numerous commonly used active ingredients classified as organophosphates (many ending in -phos, -fos, -vos, or -thion), and have a wide range of toxicity levels. These compounds are toxic to the nervous system of insects. and function by inhibiting the activity of an enzyme in the nervous system (acetylcholinesterase), leading to overstimulation and dysfunction of the nervous system (Reigart & Roberts 1999). Symptoms of organophosphate poisoning in honey bees include loss of activity, abnormal wobbly movements, lying on the back or spinning while beating wings in this position, and/or regurgitation of collected nectar (Johansen 1984; Kevan & Rathwell 1988; Riedl et al. 2006). Damage to brood and queen by exposure to microencapsulated methyl parathion or acephate (acetamidophos) have also been recorded (Riedl et al. 2006).

Neonicotinoids

Neonicotinoid insecticides target the nervous system of insects, blocking an acetylcholine receptor. They are a class of synthetic compounds based on the naturally occuring compound nicotine, itself used as an agricultural insecticide, and have become one of the most commonly used insecticide classes in recent years with compounds registered on many major crops for foliar application and/or seed treatment. Active ingredients include imidicloprid, clothiandin, thiamethoxam, acetamiprid, thiacloprid, and dinotefuran, which are sold under a variety of trade names, and all of which are classified as highly toxic or toxic to honey bees. They are systemic insecticides, meaning that the compounds are present in the plant tissues rather than just on the surface. There is evidence that pollinators may be exposed via the resources they collect, but further research is required to determine the details and how problems might be mitigated.

Research is ongoing into the role of these compounds in honey bee declines, but it is recommended that their use near bees or blooming crops or wildflowers be completely avoided. Neonicotinoid compounds may also pose a hazard if used as a seed treatment or sprayed before bloom, as they can be present in dust from seed drills, pollen, nectar, and guttation water

(Bonmatin et al. 2005; Chauzat et al. 2006; Girolami et al. 2009). Neonicotinoids are the group of pesticides commonly implicated as a contributory cause of widespread honey bee losses, including Colony Collapse Disorder, both through direct toxic action and chronic effects on the immune system. Further studies are urgently required to address sublethal and chronic effects on non-target insects, including managed and wild pollinators.

Pyrethroids

Pyrethroid insecticides are a class of synthetic compounds based on the naturally occuring compound pyrethrin, which is extracted from chrysanthemum flowers. Pyrethrin is noted for its quick 'knock-down' of insects, but the natural compound is not always lethal, and degrades readily in the environment (Reigart & Roberts 1999). Synthetic pyrethroids have been chemically stabilized to increase their persistence in field applications and/or increase toxicity. Pyrethroids are sometimes mixed with other insecticides, either in a brand-name product or tank-mixed at the application site. Symptoms of pyrethroid poisoning in honey bees include regurgitation of collected nectar (Kevan & Rathwell 1988; Riedl et al 2006).

N-Methyl Carbamates

N-methyl carbamates, or simply carbamates, are commonly used insecticides. The names of many of these active ingredients end in the suffix -carb, and the class also includes several insecticides that are responsible for many bee poisonings (carbaryl, carbofuran). Like the organophosphates, they are inhibitors of acetylcholine metabolism in the nervous system, and thus share similar symptoms (Reigart & Roberts 1999). Symptoms of carbamate poisoning in honey bees include an inability to fly in adult bees, dead brood or newly emerged workers, or queen loss. Sublethal effects on the queen have also been recorded, such as poor or erratic egg laying performance (Kevan & Rathwell 1988; Riedl et al. 2006).

Organochlorines

Many organochlorine compounds, the most famous of which is DDT, are no longer used in North America, although insecticides containing the active ingredient endosulfan are still used and sold under the trade name Thionex or Thiodan in Ontario. Symptoms of organochlorine poisoning in honey bees include loss of activity, abnormal wobbly movements, lying on the back or spinning while beating wings in this position (Kevan & Rathwell 1988; Riedl et al 2006).

Insect Growth Regulators

These compounds, of which the most commonly used active ingredient is novaluron, are analogues of hormones or other physiologically active molecules that regulate the development of immature insects. Novaluron has been found to have very low toxicity to adults of several bee species, including honey bees, in laboratory toxicological studies (Scott-Dupree et al. 2009). However, it has been implicated in impaired brood development in honey bees in the field (Riedl et al 2006).

6.0 Arrangements for Pollination Services

The information provided in this section is for the purpose of guidance only, and is not intended to substitute for the services or advice of a qualified attorney.

6.1 Obligations of beekeepers and growers

In its most basic form, a pollination agreement means that a beekeeper agrees to place their pollinators on the property or leased land of a grower during the bloom of their crop, in order to pollinate that crop. For their part, the grower agrees to pay the beekeeper a sum of money, usually on a per-hive basis. It is best to begin the arrangements for pollination service for the spring before the beginning of winter, in order that the beekeeper can adequately prepare, and ensure the availability of pollinators for the grower.

Many beekeepers and growers prefer to do business on the basis of a handshake, while others prefer the protection from legal and liability issues that a formal contract can offer to both sides. It is important to realize that a contract does not imply mistrust of either party by the other, rather it codifies their arrangement in the face of uncertainty, and affords peace of mind to both. Without a contract, if a business relationship sours the involvement of banks and lawyers can complicate matters very quickly, and usually to the detriment of both parties to the original agreement. At a minimum, the contract should include information addressing the following points:

- **Addresses**
  - Physical and mailing addresses and telephone numbers of the beekeeper and the grower.
  - Physical location of the crop where the pollinators will be deployed (address, or coordinates).
- **Term of the Contract**
  - Because bloom has variable and uncertain timing, the grower and beekeeper should agree to a notice period (for instance, 48 hours) within which bees must be on the crop after the grower has informed the beekeeper that the crop has reached the appropriate point in the bloom (for example, 25%), rather than a particular date. Alternatively, a target date for deployment can be agreed upon.
  - The length of the deployment should also be specified, or a notice period (for instance, 48 hours) within which bees must be removed from the crop after the grower has informed the beekeeper. A maximum length of deployment should be specified, after which the bees are removed or a new contract negotiated.
- **Payment**
  - Price per hive for the duration of the deployment.
  - Number and location of hives on the grower's property.
  - Due date for payment, and any additional charge for late payment if applicable.

  - Any bonuses or penalties for deviations from minimum colony strength should be explicitly stated.
  - Any compensation to be paid to the beekeeper for additional movement of bees requested by the grower, for instance if the grower wishes to spray pesticides on the crop.
- **Responsibilities of the Beekeeper**
  - The beekeeper agrees to deploy and remove bees within an agreed time period (for instance, 48 hours) when notified to do so by the grower.
  - The beekeeper will provide colonies of a specified minimum strength (see Section 4.4). This is typically described in terms of number of chambers ("storeys") of each hive, number of frames covered with adult bees, and/or number and area of frames with brood.
  - The beekeeper will open hives and demonstrate that minimum strength conditions have been met upon the grower's request. Alternatively and by mutual consent, a third party qualified to do so may certify minimum strength and provide documentation that it has been met.
  - The beekeeper will maintain the colonies at this required strength for the duration of the contract.
- **Responsibilities of the Grower**
  - The grower will provide clear instructions and suitable site(s) where bees are to be deployed. The grower will also permit access to vehicles and to the beekeeper for colony maintenance activities necessary during the period of deployment.
  - The grower will provide notice (for instance, 48 hours) to the beekeeper to deploy bees on the crop when an appropriate stage of bloom is reached.
  - The grower will provide notice (for instance, 48 hours) to the beekeeper to have the bees removed prior to the expiry of the contract.
  - The grower agrees to provide a source of uncontaminated water to the bees within a specified distance of the hives (for instance, 1km).
  - The grower will assume liability if the bees or equipment are damaged, destroyed, or lost (including criminal vandalism or theft by trespassers) while on the grower's property.
  - The grower will assume liability for any stinging incidents to employees or members of the public (including trespassers) while the bees are deployed.
  - The grower agrees to provide notice (for instance, 48 hours) to the beekeeper if pesticides are to be used by the grower or the grower's neighbour (if applicable) while the bees are deployed. Furthermore, if such notice is NOT given, the grower assumes liability for damage resulting from use of pesticides while the bees are present, whether through misuse of the product (i.e. application to a blooming crop), accident such as drift or equipment malfunction, or even activities of a neighbouring grower that may or may not be aware that the bees

are present.

- **Addenda**
    - Any other conditions, requested by either party, agreed to by both parties.

Additional information that may be included in a pollination contract:

- Methods for conflict resolution. Sample text used in Washington State sample contract: "If any problem arises between the parties involved in this contract that cannot be resolved, then the problem(s) shall be settled by arbitration. Each party will choose an arbitrator within ten days to act in their behalf; these two shall select a third by mutual consent and a decision agreed upon by any two of these arbitrators shall be binding. The cost of any arbitration shall be shared equally by grower and beekeeper."
- Money to be paid to the beekeeper to compensate for loss of bees if the grower is found to be in violation of the pesticide exposure clause. Definition of threshold damage at which payment is owed (i.e. 50% loss of adult bees in a hive) should be stated here.

6.2 Sample agreements and contracts

There are numerous sample agreements and contracts available online, providing variable levels of detail. Some are specific to particular areas, such as the examples from the Pacific Northwest. The states of Washington and Oregon are unusual in having legislated regulations for colony strength (see Section 4.4), and government inspectors to evaluate colony strength upon request. See Useful Links (Section 8.0) for links to examples of sample contracts.

7.0 Recommended Reading

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8.0 Useful Links

(Note: mention of particular company or organization is not intended as an endorsement or recommendation by NSERC-CANPOLIN, the University of Guelph, or OMAFRA. This table is provided as additional information only.)

LEGAL	
Bees Act - Search "bees act" for the latest consolidation on the Government of Ontarios E-laws website:	www.e-laws.gov.on.ca/navigation?file=browseStatutes&reset=yes&menu=browse&lang=en
Honey Bee Registration Form. Under the Bees Act, anyone keeping honey bees must register them with the Provincial Apiarist of Ontario	www.omafra.gov.on.ca/english/food/inspection/bees/info_registration.htm
Sample **pollination contracts and agreements.**	http://www.al.gov.bc.ca/apiculture/forms/pollination_contract.pdf http://www.beesource.com/files/pollination_contract.pdf
POLLINATION & AGRICULTURAL CONSERVATION	
Alternative Land Use Services (ALUS) is a grower-managed organization the encourages and provides funding and information for on-farm conservation projects, including pollination conservation (currently active in Norfolk County)	www.norfolkalus.com
Canadian Pollination Initiative (NSERC-CANPOLIN) is a strategic network investigating all aspects of pollination in Canada	www.uoguelph.ca/canpolin
International Bee Research Association (IBRA) is an international non-profit organization that collects and distributes information on all species of bees	http://www.ibra.org.uk
North American Pollinator Protection Campaign (NAPPC) is a non-profit organization for pollinator conservation in Canada, the United States, and Mexico	pollinator.org/nappc/index.html
Ontario Ministry of Agriculture, Food, and Rural Affairs information resource on apiculture	www.omafra.gov.on.ca/english/food/inspection/bees/apicultu.html
Pollination Canada is a non-profit citizen science organization devoted to pollinator conservation in Canada	www.pollinationcanada.ca
Seeds of Diversity is the parent organization of Pollination Canada, and a charitable organization dedicated to the conservation, documentation and use of public-domain, non-hybrid plants of Canadian significance	www.seeds.ca
The **Xerces Society** is an international non-profit organization devoted to conservation of invertebrates and their habitat	www.xerces.org

Beekeeper & Grower Organizations	
Canadian Honey Council (CHC) is the national organization of the beekeeping and honey processing industries	www.honeycouncil.ca
Canadian Association of Professional Apiculturists (CAPA) is the professional society of the Canadian beekeeping industry	www.capabees.com/main/news.php
Ontario Beekeepers Association is the professional society of the Ontario beekeeping industry	www.ontariobee.com
Apimondia is the International Federation of Beekeepers' Associations and other organisations working within the apiculture sector	www.apimondia.com/en
Mid-Atlantic Apiculture Research and Extension Consortium (MAAREC) is an apicultural and pollination extension organization, serving the states of , with lots of useful links and information	agdev.anr.udel.edu/maarec
Ontario Berry Growers Association	ontarioberries.com
Ontario Federation of Agriculture (OFA) is a professional and advocacy organization for Ontario's farmers	www.ofa.on.ca
Ontario Fruit and Vegetable Growers' Association (OFVGA)	www.ofvga.org
Ontario Greenhouse Vegetable Growers (OGVG)	www.ontariogreenhouse.com
Ontario Processing Vegetable Growers (OPVG)	www.opvg.org
The Society of Ontario Nut Growers	www.songonline.ca
Vendors - Managed Pollinators	
BeeDiverse is a vendor of mason bees for tree fruit pollination, ands sell domiciles and other accessories (British Columbia)	beediverse.com
BioBest sells a variety of biocontrol and pollination products, including bumble bee colonies (*Bombus impatiens*)	www.biobest.ca
Crown Bees is a mason bee resource. Also contains information about the Orchard Bee Association (Washington State)	www.crownbees.com
Koppert Biological Systems is a vendor of a variety of horticultural products, including managed pollinators such as bumble bees (*Bombus impatiens*, sold as Natupol®) and blow flies (sold as Natufly®)	www.koppertonline.ca/home.asp
Information about and vendors of **alfalfa leafcutter bees**:	http://umaine.edu/blueberries/factsheets/bees/300
Pollinator Paradise sells alternative managed pollinators and accessories, and consults on issues of their use (Idaho)	www.pollinatorparadise.com
Sask Leafcutters Association provides information about alfalfa seed production and management of alfalfa leafcutter bees	www.saspa.com
Vendors - Accessories	
FirmYield Pollen (seller of Bee Booster pollen dispensers)	www.firmyieldpollen.com
Contech are producers of FruitBoost and SuperBoost honey bee pheromone analogues, in addition to other products	www.contech-inc.com
Other Useful Information	
Extension publications and recent news relating to bees, beekeeping, and pollination	www.extension.org/bee_health
Koppert **Side Effects** database, describes beneficial insects and their compatibility with various pesticides	side-effects.koppert.nl/#

The Ontario Ministry of Agriculture, Food, and Rural Affairs has information on analysis of honey bees for **pesticide residues**.	www.omafra.gov.on.ca/english/food/inspection/bees/info_analysis.htm
Pesticide registration in Canada is federally regulated by the Pest Management Regulatory Agency (PMRA). A list of **pesticides registered** in Canada, together with links to registration information.	www.pesticideinfo.org/Detail_Country.jsp?Country=Canada
The Ontario Ministry of the Environment also maintains a site allowing online access to information about **registered pesticides**, including the PMRA label database	http://www.ene.gov.on.ca/environment/en/category/pesticides/STDPROD_079355.html#1
The **Pollinator Garden** gives ideas to construct your own wild bee "hotels"	www.foxleas.com/bee_house.htm
Resonating Bodies presents information and artistic projects related to native solitary bees	www.resonatingbodies.wordpress.com

9.0 Source Material

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