Food and Agriculture Organization
of the United Nations

EXTENSION OF KNOWLEDGE BASE

ADAPTIVE MANAGEMENT

CAPACITY BUILDING

MAINSTREAMING

A MANUAL ON APPLE POLLINATION

gef

UNEP

POLLINATION SERVICES FOR SUSTAINABLE AGRICULTURE

A MANUAL ON APPLE POLLINATION

Cory S. Sheffield
Royal Saskatchewan Museum (RSM)

Hien T. Ngo
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

Nadine Azzu
Food and Agriculture Organization of the United Nations (FAO)

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, ROME, 2016

ISBN 978-92-5-109171-5

Cover photos
left to right:
© N. Vereecken, © M.P. Garratt, © C. Sheffield

Back cover photos
left to right:
© C. Sheffield, © N. Azzu, © N. Azzu

This publication provides information on the management of bee pollinators in apple orchards.

The text was prepared as part of the Global Environment Fund (GEF) supported project 'Conservation and management of pollinators for sustainable agriculture, through an ecosystem approach' implemented in seven countries – Brazil, Ghana, India, Kenya, Nepal, Pakistan and South Africa.

The project is coordinated by the Food and Agriculture Organization of the United Nations (FAO) with implementation support from the United Nations Environment Programme (UNEP).

CONTENTS

LIST OF FIGURES

LIST OF BOXES

PREFACE

It is estimated that by 2050 the world population will increase by approximately 30 percent to 9.1 billion people, which will invariably increase the demand on global food supply. Meeting this challenge of addressing current and future global food demands is reliant upon our ability to sustain, or increase, agricultural food production from the same area of land in a way that does not intensify the negative impacts on the environment. To add to this, the influence of climate change on agricultural production systems and associated ecosystem services, such as nutrient cycling, pest regulation and pollination, is largely unknown.

Many innovative and feasible opportunities and methods exist that can increase food production sustainably. In this context, the management of agricultural landscapes, so as to optimize the use of natural ecosystem services, will contribute to sustainable agricultural production while maintaining and encouraging bbiodiversity. Pollinators provide an essential ecosystem service by ensuring production of fruit, seeds, nuts and vegetables; pollination services are also important for biofuel and fodder cropping systems.

Apple, as one of the most widely cultivated fruit tree crops in the world, unsurprisingly, is a top global commodity. China produces approximately half of the total apple production, followed by the United States, Turkey and Poland. Apple production depends on insect pollination - therefore, understanding pollinators, their requirements and behaviours within and around apple orchards, at both small and large-scale production levels, will allow for better pollination management strategies and increase apple production.

In its role as coordinator and facilitator of the International Pollinator Initiative (IPI) of the United Nations Convention on Biological Diversity, FAO established a Global Action on Pollination Services for Sustainable Agriculture. Within this Global Action, and through the implementation of a GEF/UNEP-supported project on the 'Conservation and Management of Pollinators for Sustainable Agriculture, through an Ecosystem Approach', FAO and its partners in seven countries developed tools and guidance for the conservation and management of pollination services to agriculture.

In April 2014, a workshop in Daman, Nepal was organized in collaboration with the GEF/UNEP/FAO Global Pollination Project, the Marin Community Foundation (United States), the Royal Saskatchewan Museum (Canada) and York University (Canada), on 'Natural pollination services for agricultural production in apple orchards in the Hindu-Kush Himalayan region'.

The objective of the workshop was to share information with apple growers and agricultural extension workers on the theory and methods involved in the discovery, encouragement, and management of native pollinators to enhance apple pollination.

Workshop participants, representing experts on apple pollination in the Hind-Kush Himalaya region came from India, Nepal and Pakistan. Following the workshop, the decision was taken to prepare an information manual on apple pollination. The present Manual is a result of this collaboration of experts.

Alison Hodder

Senior Officer, Horticulture
Plant Production and Protection Division, FAO

ACKNOWLEDGEMENTS

The idea of preparing this Manual came out of a workshop in Daman, Nepal (2014), on 'Natural pollination services for agricultural production in apple orchards in the Hindu-Kush Himalayan region'. The workshop, organized through a collaboration between the GEF/UNEP/FAO Global Pollination Project, the TOP Fund through the Marin Community Foundation (United States), the Royal Saskatchewan Museum (Canada) and York University (Canada), was attended by experts on apple pollination in the Hind-Kush Himalaya region. We would like to thank all the participants, who joined from India, Nepal and Pakistan, for their input to the workshop. We would also like to extend our special thanks to the FAO Office in Nepal, for all of their organizational support in making this workshop happen.

© FAO/M. Marzot

SECTION 1
INTRODUCTION

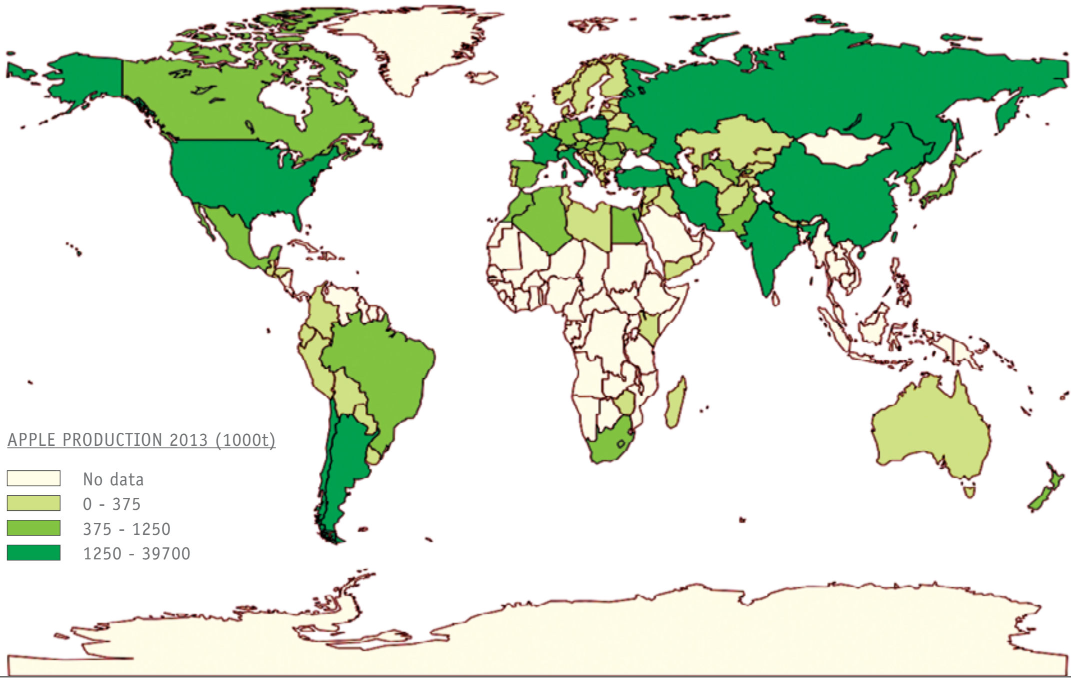
Apples (genus *Malus*, a member of the Rosaceae or rose family) have been part of the human diet for thousands of years (Hancock *et al.*, 2008), as demonstrated by the discovery of 'fossilized' fruit (presumably *Malus sylvestris*, the European wild apple) in human dwellings in Switzerland (Elzebroek and Wind, 2008). Indeed, the importance of apples to human culture and nutrition over the millennia is demonstrated by their presence in art, mythology and the religions of many regions, including Norse, Greek and European Christian traditions, as well as in the Muslim world (Hancock *et al.*, 2008). The earliest recorded cultivation practices took place in Central Asia, perhaps around the Caspian and Black seas (Hancock *et al.*, 2008), where the main wild ancestor of all cultivated apple, *Malus sieversii* (the Asian wild apple), and other wild species (including *M. sylvestris* and *M. pumila*) still grow today.

It is presumed that the place of origin and centre of diversity of the genus *Malus* is Central Asia around Turkestan, which today is Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan (Hokanson *et al.*, 1997; Harris *et al.*, 2002; Velasco *et al.*, 2010). Thus, apple trees were one of the earliest to be cultivated and over thousands of years selection has improved the fruit (Morgan and Richards, 2002; Hancock *et al.*, 2008).

Recent genetic studies suggest that the domestic apple (*Malus x domestica*), although largely originating from the Asian wild apple (Valesco *et al.*, 2010), received genetic material from several wild apple species from both Asia and Europe (Cornille *et al.*, 2012), which arrived over the trade routes and by way of human migration and settlement. Apples enjoyed today share their ancestry with several of the approximately 30 primary *Malus* species (i.e. wild apples), as a result of a long history of travel and hybridization (Hancock *et al.*, 2008). Today apple is one of the most widely grown and important tree fruit crops in temperate areas of the world (Zohary and Hopf, 2000; Cornille *et al.*, 2012) (Figure 1).

Figure 1

THE MAJOR APPLE PRODUCING COUNTRIES (SHOWN IN GREEN; DARKER SHADES INDICATE HIGHER LEVELS OF APPLE PRODUCTION).



Source: FAO, 2013 production data

Old World apple seeds first arrived in the Americas in the seventeenth century. Before that time, only crab apples were native to North America (Hancock *et al.*, 2008). The first apple orchards in North America were probably planted in New England on colonial farms in the early 1600s, but apple seeds from Europe were also spread along the trade routes of First Nation communities. Thus, orchard production in North America began and, by the mid-1800s, many apple cultivars, many of which had been newly developed in North America, were being sold from the catalogues of successful apple nurseries (Hancock *et al.*, 2008). In this way, a large industry emerged, and North America (the United States and Canada) came to lead world apple production during most of the twentieth century (Canadian Food and Inspection Agency, No Date).

Similar patterns of human migration and settlement promoted the spread and establishment of apple throughout the world. Apple seeds were carried to most areas settled by Europeans, including South Africa, where orchards were established in the mid-1600s. In the 1700s and 1800s, apples were introduced to Australia and New Zealand, respectively, with markets developing later in South America (Hancock *et al.*, 2008).

Apple production, in the quantities seen today, required intensive research on cultivar development and selection (e.g. for localized climate, human taste preferences, pest and disease resistance), propagation methods and planting strategies. Intense management of apple as a horticultural crop is recent, with much research on the development of new cultivars, and advancement in production occurring within the last half century (see Westwood, 1978; Childers, 1983; Morgan and Richards, 2002; Hancock *et al.*, 2008; Brown, 2012). Apple production has expanded considerably, by approximately 50 percent over the last 20 or more years (Brown, 2012), particularly in China, where production has grown rapidly from about 5 million tonnes in 1990, to 17 million tonnes in 1997 (Papademetriou *et al.*, 1999), to over 30 million tonnes today.

Currently, China dominates global apple production, where about five times more apples are grown than for the next leading producer, the United States which, as stated above, led world production during the last century, and accounts for over 50 percent of global production (US International Trade Commission (USITC), 2010; 2011; FAOSTAT, 2015). Other major producers include Turkey, Italy, Poland, India and Iran, with other producers in South America and Central Asia (Figure 1).

Today, there are more than 6 000 apple cultivars (Hancock *et al.*, 2008), each having been developed for specific human preferences such as taste, size, different uses including cooking, eating and cider production, and for physiological reasons for example resistance to crop disease, harvest time, climate suitability and storability (King *et al.*, 1991). Apples are available year-round across the globe as a result of advancements in cold storage technology, production in both hemispheres and, in some regions such as Ecuador, at high altitudes crop production can occur twice a year because of the year-round uniform temperate conditions.

Apple breeding and development has traditionally been based on controlled cross-pollination, which results in seed formation, as a means to acquiring traits within the fruit and/or trees. Most new apple cultivars still originate as seedlings, mainly as a result of deliberate cross-pollination of varieties or cultivars that have promising characteristics (discussed below). For example, the terms 'seedling', 'pippin', and 'kernel' in the name of an apple cultivar suggest that it originated as a seedling. Less commonly, apples can form 'bud sports,' which is a morphological mutation that is clearly different from the rest of the plant and sometimes has desirable characteristics that can be used to propagate new cultivars or improved strains of the parent cultivar.

Apple seeds are unsuitable for propagation as seedlings, as apples display 'extreme heterozygosity' in that they do not breed true from their parents in displaying cultivar characteristics. For example seeds from a McIntosh apple do not grow into a McIntosh tree.

Thus, propagation of apple as a crop is not from seed, but from grafting, which is an asexual horticultural process where tissues from one plant are inserted into those of another. In this case, the stem is inserted into a suitable rootstock and the vascular tissues of both components are joined.

Reproduction and propagation have been topics of horticultural investigation throughout the long history of the apple industry (see Brittain, 1933; McGregor, 1976; Westwood, 1978; Pratt, 1988; Sedgley and Griffin, 1989; Free, 1993; Delaplane and Mayer, 2000; Sharma *et al.*, 2006). Despite this long history of research and development, there is still much to be learned about apple reproduction, including flower form and function with respect to influences upon the formation and distribution of seeds in the fruit, which contribute to fruit quality; and the reproductive requirements of new cultivars (Sheffield *et al.*, 2005).

The first objective of this Manual is to review pollination and apple flower morphology to promote better understanding. Certainly, much of the story of apple pollination - the movement of pollen from one flower to another - involves insect pollinators that transport pollen from flower to flower. This Manual summarizes basic bee biology in relation to apple, and discusses ways to maintain or improve apple pollination by considering the needs of bee pollinators. Finally, apple orchard structure and genetic composition are reviewed, and how these aspects relate to optimizing cross-pollination, fruit development and ultimately apple quality and yield.

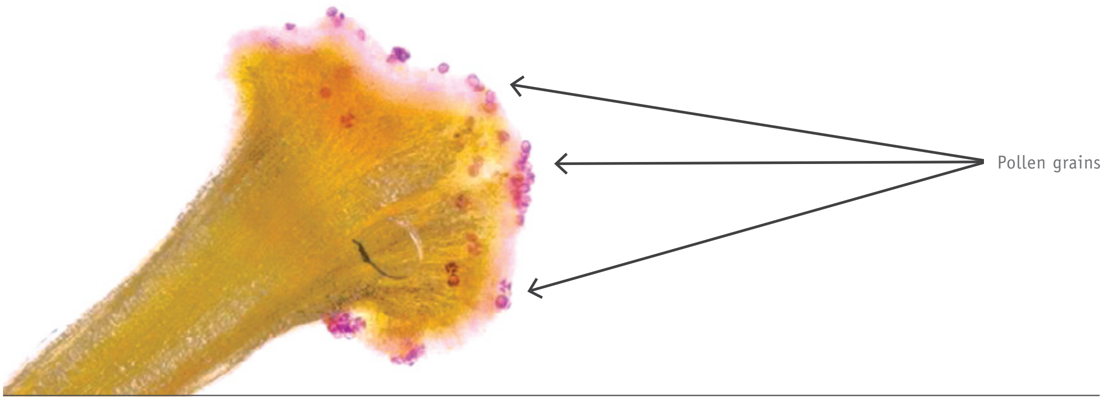
SECTION 2
POLLINATION AND APPLE FLOWER MORPHOLOGY

In order to appreciate the rationale behind options related to pollination and apple production, it is important to understand pollination, apple flower morphology and the affect these have upon each other. The development of an individual fruit is a complex process and, from the time a flower opens until the fruit ripens, several key steps must occur (Abrol, 2012). The first step, pollination, involves the transfer of pollen (i.e. the male sex cells of higher plants), from the anther to the stigma (i.e. the pollen-receiving part of the female sex organ, or gynoecium) (see Figure 2).

Pollination does not refer to the subsequent steps that include pollen tube growth down the style and the resulting fertilization of the ovule, or the development of seeds or the fruit(s), which are all components of fruit production that occur after pollination. As such, it is possible to have excellent pollination, represented by a sufficient amount of pollen

Figure 2

POLLINATION OCCURS WHEN POLLEN GRAINS ARE DEPOSITED ON THE STIGMA(S) OF A FLOWER.



Source: Danae Frier

being delivered to the stigma, yet fail to have fruit develop. When this happens, it is often the pollinators - bees, butterflies, flies and other flower-visiting animals - that are held responsible for poor fruit yield in crop systems. Sometimes this is the case if climatic conditions have been poor during flowering, which reduces pollinator activity thereby preventing pollination, or if the pollinators are not present and/or abundant enough to provide full pollination to all the flowers, thus resulting in a pollination deficit.

Pollinator abundance can be affected by several factors, which are discussed below, that include the lack of floral or nesting resources required by insect pollinators in the local landscape, and the use of agricultural chemicals. Non-pollinator-related factors are also important for fruit development and, in some cases, more so. These include pollen viability and the genetic compatibility of pollen(s) from the cultivars in an orchard, both of which can reduce fertilization and subsequent fruit set, leading to reduced yield and fruit quality (Kendall, 1973; Jana, 2001; Kron *et al.*, 2001a; 2001b; Sharma *et al.*, 2004; 2006).

Many fruit crops, including apple, require cross-pollination meaning that in order to set fruit they need to receive pollen from a genetically different compatible individual (Figure 3). Therefore, ‘pollenizers’ (i.e. compatible pollen donors) or a mix of compatible cultivars are required to produce apples (Brittain, 1933; Kendall, 1973).

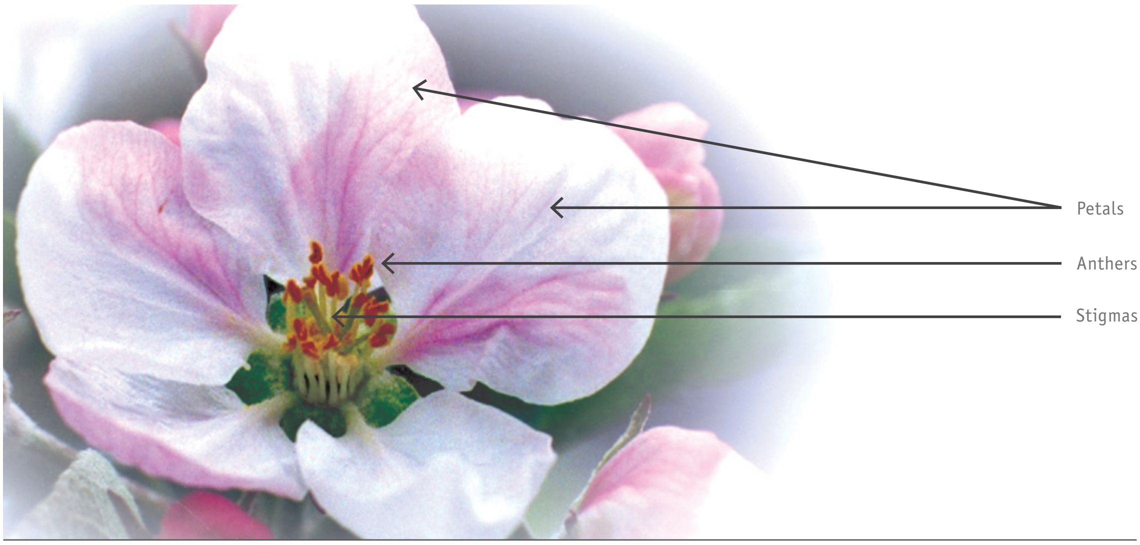
Figure 3

FLOWERS FROM DIFFERENT APPLE CULTIVARS CAN LOOK DIFFERENT AND CAN PRODUCE POLLEN THAT IS GENETICALLY DIFFERENT.

Source: Cory Sheffield

Figure 4

A TYPICAL APPLE FLOWER, SHOWING THE MAJOR EXTERNAL PARTS RELATED TO POLLINATION.



Source: Cory Sheffield

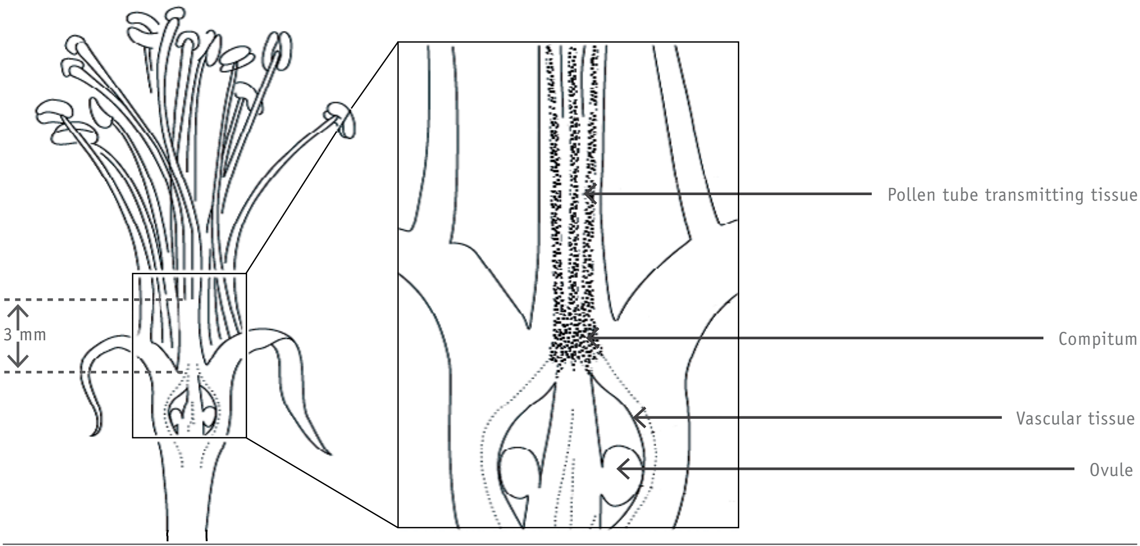
In this section, flower and fruit morphology is discussed to further understanding of how pollination is linked to fruit development in apple. Apples have perfect flowers, meaning both female and male reproductive organs are present that contain the ovules and produce the pollen, respectively (Figure 4).

The female organ of the flower, the gynoecium, comprises five carpels; each has a stigma, a style and an ovary (Weberling, 1989; Endress, 1994; Raven *et al*., 1999) that normally contain two ovules (McGregor, 1976; Westwood, 1978; Faust, 1989; Free, 1993). In apple, the styles have a solid core of transmitting tissue through which the pollen tubes grow among or between cells (Cresti *et al*., 1980; Sedgley, 1990), and each style is basally fused with the other styles along a portion of their total length (Figure 5). Apple flowers, therefore, have been described as syncarpous, or as having fused carpels, though the level of inter-carpel communication by way of the compitum, which is a shared area of internal communication (see Figure 5), varies among cultivars.

Until recently (see Sheffield *et al*., 2005), the apple flower carpels were thought to be 'imperfectly syncarpous', or without a compitum (Carr and Carr, 1961; Cresti *et al*., 1980; Anvari and Stösser, 1981; Pratt, 1988; Weberling, 1989), with each fruit being able to form up to ten seeds (i.e. two seeds per carpel), with variations among cultivars (McGregor, 1976; Westwood, 1978; Faust, 1989; Free, 1993). Where cultivars have flowers with no compitum, viable pollen

Figure 5

THE INTERNAL STRUCTURE OF A MCINTOSH FLOWER, SHOWING THE POLLEN TUBE GROWTH PATHWAY (I.E. STIPPLED AREA) DOWN EACH STYLE.



Source: adapted from Sheffield *et al.*, 2005

grains must be transferred from a compatible cultivar to each of the five receptive stigmatic surfaces (Torchio, 1985) to produce an apple with a full complement of seeds (i.e. seed(s) present in each carpel). For these cultivars, differences in the levels of pollination among the five stigmas can directly affect fruit quality and quantity, because of the resulting variable production and distribution of seeds (Carr and Carr, 1961; Sheffield, 2014).

Many apple cultivars, however, are known to possess a compitum, as discussed below, which allows for inter-carpel growth of pollen tubes (Sheffield *et al.*, 2005). As such, an individual stigma can be pollinated and still result in full fertilization with seeds being produced and evenly distributed within the fruit. The number and distribution of seeds within a developing apple affects its shape and weight (Brittain, 1933; Brittain and Eidt, 1933; Free, 1993; Brault and de Oliveira, 1995; Keulemans *et al.*, 1996; Sheffield, 2014).

Furthermore, flowers and developing fruit that are not pollinated, or are poorly fertilized, usually drop soon after they have bloomed (Free, 1993). Most immature fruit dropped within a few weeks of flowering typically have fewer developing seeds than fruit that remains on the tree (Brittain and Eidt, 1933; Brain and Landsberg, 1981), although the relationship is not always straightforward (Lee, 1988; Ward *et al.*, 2001), as many mature fruits do not contain a full complement of seeds (Sheffield, 2014).

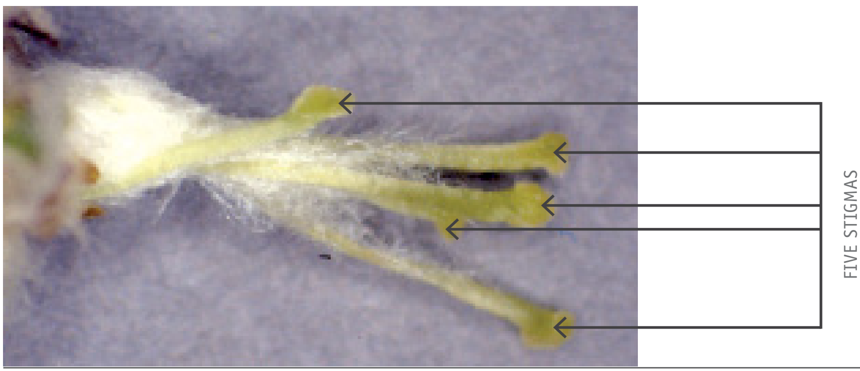
Several factors may result in pollination differences among the five stigma surfaces of apple flowers. Not all surfaces will receive pollen if the stigmas are separated from each other at the time a pollinator visits the flower, or if the length of each style is different because the gynoecium has been damaged or deformed (Figure 6). These morphological factors could result in asymmetric fertilization and seed distribution in cultivars with imperfectly syncarpic flowers (i.e. those without a compitum), which can lead to early fruit drop or misshapen fruit.

Pollinator foraging behaviour may also be a factor in contributing to asymmetric pollination. Among apple cultivars, the colour and external form of apple flowers can vary considerably (refer to Figure 3) (Stott, 1972; Kendall and Smith, 1975; Ferree *et al.*, 2001); some of these differences can negatively affect the foraging behaviour of pollinators and can lead to inefficient or inadequate pollination.

The structure of the apple flower facilitates pollinators, namely bees, as they access the floral nectaries and move through the anthers, where they come into contact with each of the stigmas (i.e. top-working bees) (Figure 7). In contrast, they can enter through the side of the flower, where they access the nectaries through the base of the anthers (i.e. side-working bees). Side-working bees are less likely to touch the stigma than top-working bees (e.g. for honey bees, side-working behaviour is well documented in 'Delicious' apples (see Robinson, 1979; Degrandi-Hoffman *et al.*, 1985; Schneider *et al.*, 2002). The differences in internal morphology, as outlined above, particularly the presence of a compitum (Sheffield *et al.*, 2005), may differ among cultivars. In cultivars without a compitum, the pollen must be distributed evenly among the stigmas in order to obtain a full complement of seeds (Visser and Verhaegh, 1987).

Figure 6

A DEFORMED APPLE FLOWER, WITH UNEVEN STYLE LENGTHS, RESULTS IN STIGMA SURFACES THAT ARE NOT EQUALLY ACCESSIBLE TO POLLINATORS.



Source: Cory Sheffield

Figure 7

A SOLITARY BEE (*ANDRENA* SP.) COVERED WITH POLLEN WORKING THE CENTRAL PART OF AN APPLE FLOWER.

Source: Cory Sheffield

Intensive apple cultivar development, which has contributed to variations in fruit morphology (Bultitude, 1983), has also likely resulted in the modification of the external and internal floral form, with resulting implications for pollination, seed set and fruit quality (Sheffield *et al.*, 2005; Sheffield, 2014). Considering the over 6 000 known cultivars, and the trend for developing more, it is important to fully understand all factors that affect apple fruit yield and quality, which are not always linked to lack of pollination.

Despite this, pollinator foraging behaviour, floral attractiveness to pollinators, pollination requirements (i.e. compatibility), pollen viability, pollen tube growth pathways, and other flower-based characteristics of the resulting cultivars have seldom, if ever, been considered or selected for during new cultivar development. All of these factors ultimately influence fruit quality and yield in apple. With recent knowledge of the cultivated apple genome (Velasco *et al.*, 2010; Evans *et al.*, 2011), it may soon be possible to select from lineages having both favourable floral features for pollinators to promote pollination, in addition to other characteristics of interest.

SECTION 3
CONSERVATION OF WILD BEES FOR APPLE POLLINATION

Bees (Hymenoptera: Apoidea, Apiformes) are specialized wasps that have relinquished their habit of hunting insects and other arthropods to secure food for their offspring and, instead, have become vegetarian, using pollen, nectar and other floral resources for food. As such, bees are entirely dependent on flowering plants, and the presence and abundance of these insects within any habitat is largely dependent on the availability of floral resources. This dependence on flowers makes bees the most important pollinators (Figure 8), and apple, like many of the most important food crops, requires pollination by bees to produce fruit (Free, 1993; Delaplane and Mayer, 2000; Sharma and Gupta, 2001; Sharma *et al.*, 2012).

Figure 8

A SOLITARY BEE (*ANDRENA* SP.) LOADED WITH POLLEN VISITING AN APPLE FLOWER.

Source: Sean Michael Webber

Globally, the honey bee (*Apis mellifera*) is considered to be the most important pollinator of apple, and is managed as a commercial pollinator in all apple-growing regions of the world (Brittain 1933; Free, 1993; Gupta *et al.*, 1993). Managed honey bee colonies are moved into apple orchards for pollination during the flowering period, and then removed to lower the risk of exposure to agricultural chemicals and other management practices following pollination. This practise also allows for the colonies to be placed in other crop settings, or in habitats rich in other floral resources.

This general pattern is followed in almost all settings where honey bees are used as commercial pollinators. The future availability of managed honey bees to meet crop pollination requirements has, however, become uncertain largely because of rapid colony losses over the last decade, which have been attributed to Colony Collapse Disorder (CCD). Currently, the losses sustained by honey bee industries have varied from region to region, possibly as a reflection of beekeeping management methodologies or pollination services, and/or the extent of agrochemicals used near colonies (Pettis *et al.*, 2013).

Several factors are known to cause losses in managed honey bees including, in some areas, specific aspects of management such as long distance, migratory beekeeping as well as high parasite and pathogen levels. Other factors are known to have a more general, though no less severe, negative effects on all pollinators, including honey bees, such as the use of some pesticides, invasive species, and habitat loss, including reduction and/or loss of floral resources and others required in the local habitat.

Historic evidence suggests that wild bee species make an important contribution to crop pollination (see Brittain, 1933; Kendall 1973; Ganie *et al.*, 2013), and recent data suggests that wild bees may be responsible for large proportions of the pollination services that have been attributed to managed honey bees (Breeze *et al.*, 2011). The consensus is that, in almost all cases, pollination services are better when there is high pollinator diversity and abundance, and that in some cases wild bees are better pollinators than honey bees per single flower visit (see Javorek *et al.*, 2002; Garibaldi *et al.*, 2013).

It is known that managed honey bees continue to be the most valuable contributor to crop pollination, but it is also becoming clear that they should not be the only species of pollinator considered when it comes to discussing pollinator conservation and/or encouragement. To ensure that future crop pollination services are met, there is not only the need to ensure that the main managed pollinator remains a viable component of agriculture, but also that native pollinator populations are kept intact (Vaughan *et al.*, 2007). This includes the indigenous *Apis* species found in many Old World apple-growing regions and a large number of other pollinating taxa (Radar *et al.*, 2015).

Globally, there are over 20 000 species of bee (Michener, 2007), and many, but not all may show promise for future encouragement and/or commercial management of pollination. An obvious exception, for instance, are the cleptoparasitic bees, the females of which do not collect pollen for their own offspring, but instead lay their eggs in the nests of other bee species. As these bees only visit flowers for nectar, not pollen, their potential for significant pollination is limited. However, a cleptoparasitic life style is only one of several found in bees. Thus, diversity of traits related to life history is high among bees, and knowledge of the biology of local species can provide insights into the best ways they can be conserved and encouraged, and hint at the likelihood of the potential for the management of bees as crop pollinator[1].

3.1 NESTING BIOLOGY

Generally, the nesting biology of bees dictates how easy it is to encourage them to nest within a habitat and provide pollination services to crops. For instance, cavity-nesting bees will often accept a range of natural or artificial nesting substrates within the local habitat, and all species that are presently managed globally for pollination share this nesting habit. These include the highly eusocial (i.e. living as colonies throughout the year) honey bees, *Apis mellifera* and *A. cerana*, which naturally nest in hollowed-out trees or other similar large cavities; other species of *Apis* nest in the open (Alexander, 1991).

A range of artificial cavities, commonly called 'hives', have been developed for use around the world to encourage honey bees with this nesting habit (see Crane, 1999), as they have made harvesting honey and wax relatively easy (Figure 9). Subsequently, these managed hives have facilitated the use of honey bees for pollination, making them the most important managed pollinator of all crops. Similarly, some species of the closely related, highly eusocial stingless bees (Meliponini) are also kept in 'hives' in tropical areas for similar reasons (Kwapong *et al.*, 2010). As both groups make and store honey, there is a long history of close association with their human beekeepers. Stingless bees are also important pollinators of crops (Heard, 1999).

---

[1] Of interest could be guidance on the natural history of wild bees and their potential exposure to pesticides, which can be found in the FAO publication 'Pollinator Safety in Agriculture'. (Available at: http://www.fao.org/3/a-i3800e.pdf, from the website: www.fao.org/pollination/resources).

Figure 9

"BEE VILLAGE" MUD HIVES DESIGNED BY THE YS PARMAR UNIVERSITY OF HORTICULTURE AND FORESTRY, SOLAN (HP) TO REVIVE DECLINING INDIGENOUS BEES (*APIS CERANA*) IN KULLU VALLEY, HIMACHAL PRADESH, INDIA.

Most bumble bees are primitively eusocial, with a solitary stage during the life cycle of the mated queen; the exceptions include the social parasitic bumble bees of the subgenus Psithyrus that use colony-building bumble bee species as hosts. In temperate regions, where bumble bees are most common, colonies do not store honey in their nests for the winter months, as most of the colony, excluding new queens, dies off towards the end of the active season.

In the wild, newly emerged queens will select abandoned rodent burrows, cavities in trees and other similar places to start a colony. Some bumble bees may accept artificial nesting cavities (Fye and Medler, 1954; Donovan and Wier, 1978; Kearns and Thomson, 2001; Evans *et al.*, 2007) if they are large enough to sustain colony growth throughout the summer. The acceptance of such artificial nesting substrates has facilitated detailed studies of bumble bee colony life (see Hobbs *et al.*, 1962). More recently, artificial bumble bee colonies have been made available year-round for crop pollination (Van Heemert *et al.*, 1990; Thorp, 2003). This means that some species of bumble bee are ideal for year-round production of greenhouse crops in temperate parts of the world, and for field crops that are better pollinated by bumble bees; the crop pollination services resulting from this industry are substantial.

In addition to these social species, many solitary bees nest in a variety of smaller, pre-existing cavities. In natural settings, such nesting cavities include emergence holes of wood-boring beetles and other similar insects, within pithy plant stems, abandoned snail shells, or crevices under stones (Michener, 2007; O'Toole, 2013). The abundance of these cavities, in most terrestrial habitats, contributes to the diversity of these bees within a given region.

Conversely, habitats lacking such potential nesting sites will have a lower diversity and abundance of these bees (Sheffield *et al.*, 2008a; 2013) as the availability of nesting sites is one of the main factors limiting populations of some bee species. However, as with the social species mentioned above, many cavity nesting bees will accept artificial nesting substrates (Krombein, 1967; Sheffield *et al.*, 2008a), especially masons of the genus *Osmia*, and leafcutter bees of the genus *Megachile*, which are among the most promising wild bees for management as crop pollinators. In fact, one such species, the Alfalfa Leafcutter Bee (*Megachile rotundata*) is second only to the honey bee for the extent of its use as a pollinator (Pitts-Singer and Cane, 2011). By providing nesting sites, solitary cavity nesting bees can be encouraged to nest in a range of habitats (Sheffield *et al.*, 2008a). Moreover, artificial nests facilitate the collection of important biological data on the occupants that are required for understanding factors affecting their diversity, their specific requirements or partialities (see Sheffield *et al.*, 2008a), their floral preferences (see Cripps and Rust, 1989a and b; MacIvor *et al.*, 2014), and nesting associates (see Krombien, 1967; Sheffield *et al.*, 2008a; Barthélémy, 2012).

Cavity nesting bees use a range of natural, pre-existing cavities for nesting, and agricultural landscapes containing woodland or other non-managed habitat adjacent to crop systems often have more diverse and abundant bee communities (see Watson *et al.*, 2011), as they provide ample nesting habitat (Sheffield *et al.*, 2008a; 2013). Consequently, crops with natural habitat nearby receive better pollination (Morandin and Kremen, 2013).

Many bees will nest in any readily available sites, and thus accept any suitable cavity. Therefore, increasing the number of available nesting sites may be as simple as leaving rock piles, old tree stumps, or other substrates that can form large cavities, or using a drill to create smooth sided, closed-ended cavities in trees, fence posts, or wooden blocks. Artificial nesting blocks can provide a range of nests in habitats lacking natural woodland borders (see Krombein, 1967; Sheffield *et al.*, 2008a; Barthélémy, 2012). In many habitats, this can increase the diversity and abundance of solitary pollinators.

Though ground nesting is more common in bees (Michener, 2007), species that have this trait are more difficult to manage for pollination. In general, it is very difficult to provide nesting substrate for these bees, though some success has been met with a few species, including the sweat bee *Nomia melanderi* as an alfalfa pollinator (see Mayer and Johansen, 2003; Cane, 2008). These bees can be encouraged to nest by preparing soil beds of suitable depth and chemistry; their nesting preferences and general biology are well known because of its contribution to alfalfa production. This is a general trend with all managed bees – details of all aspects of their life, nesting biology, floral preferences, natural enemies, are required to understand how to promote them as pollinators. Currently, the nesting biology of most bee species, especially those that nest in the ground, remains poorly studied.

Generalities can be made regarding nesting preferences for ground-nesting bees. It is known, however, that some species show strong preferences for soil type and characteristics, slope, aspect and depth (Cane, 1991). It is possible to provide appropriate habitat to encourage ground-nesting bees by leaving natural habitat intact for nesting. Without having a detailed knowledge of the requirements of most species, it is more practical to conserve areas that are likely to contain nesting habitat adjoining crop settings. This may include bare soil patches, mounds of earth, or cut banks. Most local bee faunas, regardless of nesting habits, will be more diverse and abundant if natural nesting habitat is conserved and promoted. Therefore, cropping systems bordering natural habitat that is rich in bee-required resources will receive better pollination (Ricketts *et al.*, 2008; Carvalheiro *et al.*, 2010).

3.2 FOOD PLANTS FOR BEES IN APPLE ORCHARDS

Despite the known benefits of adjacent natural habitat on crop pollination, because of housing and the support of more diverse and abundant bee communities (Ricketts *et al.*, 2008; Carvalheiro *et al.*, 2010), often habitats surrounding the crop of interest are found to be highly modified, as they usually contain other crops, and they may not provide suitable nesting sites or food resources for bees (Sheffield *et al.*, 2013). Non-crop trees that may provide possible nesting sites, and/or serve as food plants for bees, are often removed from areas adjacent to crop settings as they are thought to serve as potential sources for pest species or limit machinery access to the crop(s). In addition, non-crop food plants are often removed from areas adjacent to crops as they are suspected of competing with the crop for pollinator visits, for water, and/or soil nutrients.

Wild bees often have an active flight period that is considerably longer than the flowering period of crop plants. These crops may offer bees a rich source of floral resources for a short period, and then very little thereafter (Peters *et al.*, 2013). This scenario affects female bees nesting in these habitats, and their fecundity is seldom maximized. Social bees, such as bumble bees and wild honey bees, may be particularly negatively impacted by this scenario, as they require food resources throughout colony development in temperate zones, and most of the year in equatorial areas.

Crop settings with plenty of additional food plants can support larger bee communities and result in more fecund females (Sheffield *et al.*, 2008a and b), which will increase the quantity of bees for pollination in subsequent years. In order to have relatively stable populations of wild pollinators, it is important to provide additional food plants throughout the growing season (Abel and Wilson, 1998; Sheffield *et al.*, 2008b; Hannon and Sisk, 2009; Ganie *et al.*, 2013; Korpela *et al.*, 2013; Peters *et al.*, 2013; Saunders *et al.*, 2013; Blaauw and Isaacs, 2014), especially when the target crop is not in bloom.

Additional food sources for wild pollinators can be provided by leaving adjacent natural habitat that is rich in natural floral resources, or by engaging in active bee conservation and management practices, where additional food plants are established to increase bee fecundity. Sheffield *et al*. (2008b) established lupine (genus *Lupinus*) beds in apple orchards in eastern Canada, and found that the presence of these plants, where lupine flowering occurred after apple blooms, more than doubled the fecundity of nesting bees than in orchards without them. The result was a net growth of the bee population (Sheffield *et al.*, 2008b). It is now known that non-crop flowers adjacent to or within crop systems, serve as food plants for many beneficial insects that supply pollination (Potts *et al.*, 2003; Morandin *et al.*, 2011; Miñarro and Prida, 2013; Blaauw and Isaacs, 2014) and can, in some cases, act to increase other beneficial species that serve as biological control agents of pest species (Thies and Tscharntke, 1999; Landis *et al.*, 2005, 2012; Isaacs *et al.*, 2008; Blaauw and Isaacs, 2012). Thus, the success of pollination and other beneficial ecological services are strongly influenced by how the areas adjacent to the crop are managed (Morandin and Kremen, 2013; Saunders *et al.*, 2013; Ekroos *et al.*, 2014). The benefits are not limited just to pollination.

3.3 AVOIDING AGRICULTURAL CHEMICALS

All bees within agricultural landscapes are negatively affected by the use of chemicals to control pests (see Tasei *et al.*, 1987; Ladurner *et al.*, 2005; Abbott *et al.*, 2008; Valdovinos-Núñez *et al.*, 2009; Brittain and Potts, 2011; Gradish *et al.*, 2012a and b; Blacquiere *et al.*, 2012; Henry *et al.*, 2012; Krupke *et al.*, 2012; Whitehorn *et al.*, 2012; Biddinger *et al.*, 2013). Bees can come into contact with these chemicals in many instances, for example through the flowers of crop plant(s), the respective floral resources collected, flowers within the field and adjacent habitats, and/or directly at the nest site (see Moroń *et al.*, 2012; 2014). There are additional risks for most cavity nesting megachilid bees as they collect, rather than secrete, nesting materials such as leaf pieces, masticated leaf fibres, mud or pebbles, which increases the risk and frequency of additional exposure to contaminants in these settings (see Krupke *et al.*, 2012; Moroń *et al.*, 2012; 2014).

Agricultural chemicals, such as fertilizers and pesticides, are a significant part of food production, especially at the large scales in which farms operate today. In addition, current farming practices use vast quantities of water and natural soil nutrients. These practices commonly create ideal circumstances for pest outbreaks. Many natural ecosystem services such as pollination, biological pest control, soil building and maintenance, and water provision and purification are provided by adjacent natural habitat. Employing agricultural practices that manage these ecosystem services can contribute to reducing dependence on external chemical inputs for food production.

There is still strong reliance on chemicals for food production in most agricultural areas of developed countries, but several management options are available for apple production that can help maintain fruit yield and quality while minimizing the impacts of the chemicals on bees (Reganold *et al.*, 2001). Organic and Integrated Fruit Production (IFP) offer many benefits over conventional orchard production and are considered to be more ecologically friendly. Integrated Fruit Production is the production of high-quality fruit under ecologically safe methods, where an attempt is made to minimize chemical inputs and obtain the least toxic option (Cross and Dickler, 1994; Sansavini, 1997). Reganold *et al.* (2001) compared several criteria of production methods for orchard crops, and found that alternative methods of crop production were comparable, or better, than those of conventional methods. Other studies have supported this finding and have demonstrated that non-conventional methods of production, including organic farming, typically are better for beneficial insects and non-target organisms (see Prokopy, 2003; Peck *et al.*, 2006; Ganie *et al.*, 2013).

In circumstances where pesticides, or other chemicals, must be used it is important to follow label recommendations for their proper use and timing, such as in the late evening for non-crepuscular pollination groups, night time or off-bloom times, and limit area of spraying to maximize the efficiency of controlling target groups, while keeping in mind that if there are guidelines on the label for bees, these may only be applicable to honey bees and may not be entirely relevant to wild bees. This may mean creating buffer zones for wild bee pollinators, so as to protect nesting populations from drifting spray, which can be minimized by calibrating equipment, spraying close to the crop (no aerial spraying) and spraying when there is no wind.

Moreover, artificial nests should be placed where contact with chemicals is minimized (see Sheffield *et al.*, 2008b). The choice of chemicals used is also an important consideration. Application of pesticides should not follow a schedule, but rather be based on the presence or levels of pests (i.e. acceptable thresholds) to reduce the frequency of unnecessary spraying or application.

Certainly, toxic chemicals should never be applied to the target crop during bloom. Bee-friendly products, such as lures or pheromone traps, should always be chosen in preference to chemicals with known and unacceptable toxicity.

SECTION 4
POLLINATION AND ORCHARD STRUCTURE

Apple production requires pollination by bees (Brittain, 1933; Dulta and Verma, 1987; Free, 1993; Gupta *et al.*, 1993), although pollination events do not necessarily ensure fruit production. As mentioned in the previous sections, cross-pollination (i.e. pollen from different, genetically compatible cultivars) is required for fertilization to occur in most apple cultivars. To ensure that fertilization is likely, several aspects of apple production need to be considered.

4.1 FLOWERING PERIOD AND GENETIC COMPATIBILITY

Many cultivars are grown in every apple-growing region and the flowering period of each, for example timing of flowering, start time, duration, timing of full bloom and when petals fall, can vary with respect to type and local geography. The flowering period of any apple cultivar can vary from year to year, based on weather conditions in the months leading up to bud break. Flowering periods, thus pollen availability, of co-flowering cultivar(s) and/or compatible pollenizers are important for fruit production. The mixture and arrangement of apple cultivars grown within an orchard should be chosen to provide sufficient and compatible pollen for successful fruit production and, therefore, each flowering period should overlap sufficiently to ensure that pollen availability and stigma receptivity occur at the same time. Only in this way will pollen from one cultivar be received by another.

Historically, pomologists would produce diagrams of recommended crosses and cultivar mixes, linking specific cultivars suitable for planting with each other to serve as pollen donor and recipient. These diagrams were useful as they provided apple growers a list of options for their own orchards (see Brittain, 1933). However, with over 6 000 cultivars, and new cultivars continuously being developed, it is not always clear which cultivars should be planted together so as to obtain ideal pollen mixtures. In fact, several key elements of the reproductive requirements of apple cultivars are seldom researched as they are being developed, including suggestions for pollenizor cultivars (Sheffield, 2014). Nonetheless, major apple cultivars can be grouped according to their respective flowering times, for example early flowering, mid-season, mid/late season or late flowering, though these need to be considered depending on geography and climate. Orchard design should contain co-flowering, genetically compatible apple cultivars to maximize potential fruit production.

4.2 POLLINATOR BEHAVIOUR AND ORCHARD STRUCTURE

Of the estimated 20 000 species of bees found around the world (Michener, 2007), only a small proportion are known apple pollinators. The bee species involved in apple pollination differ among apple-growing regions, and within regions of the countries that grow apples. The exception is perhaps the honey bee, *Apis mellifera*, which is the most important, managed pollinator in the world.

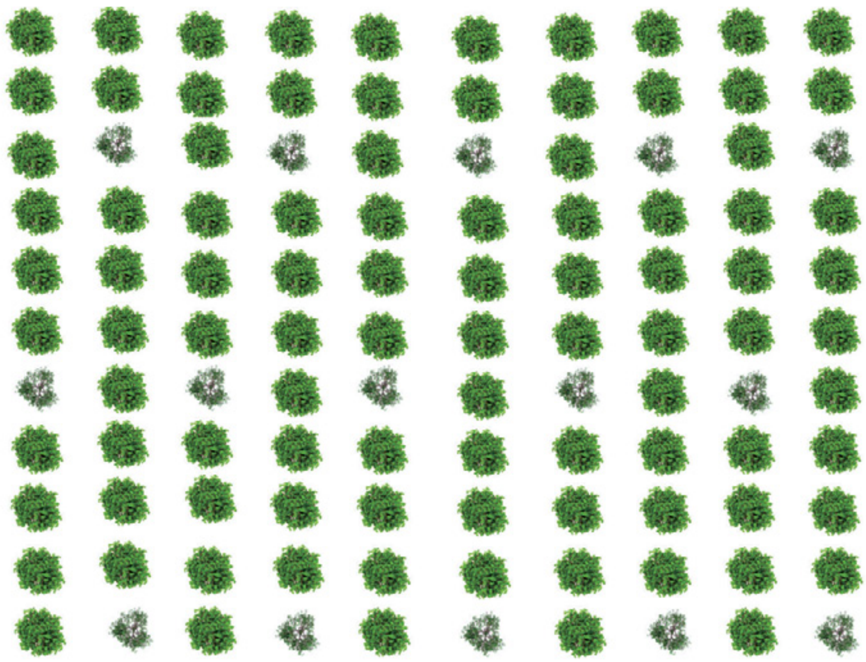
Honey bees make a very large contribution to apple pollination whenever they are used and, in most apple growing regions, it is recommended that they are present in orchards during flowering. This is especially important in orchards where other native bee species may not be present in high enough numbers to achieve adequate pollination. There are several reasons for potentially low numbers of naturally occurring apple pollinators, including the natural features of the region, but also agricultural practises which may strongly affect local bee communities such as the use of agricultural chemicals, see above.

Orchards vary greatly in size, shape, age structure of trees, tree density, tree-training and support systems; for example standard planting, high density or trellis planting systems (Robinson *et al*., 2013) and in the composition and location of the trees. In most apple orchards, row and tree spacing must be sufficient to allow farm machinery to enter, including sprayers and mowers and to accommodate harvest. To facilitate harvesting, a solid block of one cultivar may be convenient so as to concentrate the fruit-ripening period of that cultivar. Furthermore, aspects of pruning and thinning prior to fruit harvest may be easier if the orchards are set up in blocks. However, as discussed above, this is problematic for ensuring cross-pollination.

The main solution to this problem is to place single trees of a selected pollenizer cultivar, or crab apple trees, as they serve as universal pollenizers within the rows (Figure 10). A recommended pollenizer arrangement within a single row has a ratio of about 1:7, which is one pollenizer tree for every eighth tree, see Figure 10. This layout can vary depending on the varietal vigour,

Figure 10

RECOMMENDED ORCHARD STRUCTURE WITHIN A SOLID BLOCK OF THE TARGET CULTIVAR (GREEN TREES), WITH POLLENIZOR CULTIVARS SUCH AS CRAB APPLE PLACED UNIFORMLY THROUGHOUT.



Source: Cory Sheffield

the rootstock, tree-density and tree-training system. In high-density plantings of more than 1 000 trees/ha, using dwarfing rootstocks, it is especially important to locate pollenizer trees uniformly throughout the orchard block to facilitate cross-pollination. This arrangement is ideal for facilitating cross-pollination as it corresponds to the movement of pollinators; bees typically move up and down rows, and across rows during single foraging trips. The likelihood of cross-pollination occurring is much higher when there is abundant donor pollen from the pollenizors and it is readily available throughout the orchard.

However, co-flowering and genetically compatible cultivars can be planted in solid rows (i.e. without individual pollenizors), but these blocks should consist of no more than four rows of each cultivar to increase the likelihood of cross-pollination (see Figure 11). It is important to keep in mind that bees typically forage most effectively in open-canopy situations, so orchards with dense tree canopies will impede bee activity, forcing bees to work down rows only, and not across them. This reduces the effectiveness of cross-pollination in orchards with several rows of one cultivar. Thus, proper tree care, pruning and density management are important not only for light penetration (photosynthesis), but also to promote bee foraging and pollination.

There are many modes of pollination, but for the purpose of this Manual, these will be simplified into two broad categories:

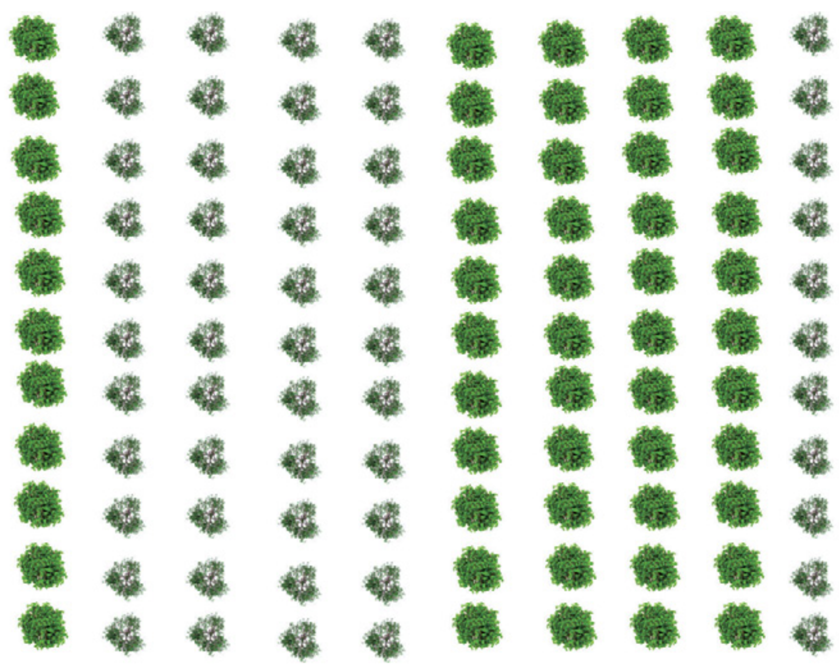
- **Self-pollination**/self-compatible; or
- **Cross-pollination**/self-incompatible.

Self-pollinated crops are those that can achieve reproductive success through pollination by transfer of pollen from the anther to the stigma of the same flower or plant, resulting in seed set and fruit development (i.e. self-fertile). Thus, self-pollinating plants may not need pollinators to achieve fertilization, but in many cases pollinators can increase the quality or quantity of self-pollinated plants by cross-pollination.

As defined above, **cross-pollination** is the transfer of pollen from anthers to stigmas of flowers of the same species, but different individual plants, using a pollination-vector such as insects, other animals, or the wind.

Figure 11

BASIC ORCHARD LAYOUT FOR POLLINATION RATIO OF 1:1 FOR TWO CULTIVARS.



Source: Cory Sheffield

SECTION 5
BEST PRACTICES

5.1 PRACTICAL MANAGEMENT OF HIVES

Honey bees (*Apis* spp.): optimizing the efficacy of managed bee colonies

When using managed honey bee colonies in an apple orchard, several measures can be adopted that can improve the performance of the colony, thus resulting in greater pollination services per hive (Free, 1993; Kakar, 2000; Delaplane and Mayer, 2000; Partap and Partap, 2002; Singh and Misra, 2007; Partap, 2012). In general, timing and hive placement (discussed earlier) is particularly important for apple pollination regardless of total orchard size, as are arrangement of apple cultivars and pollenizers within the orchard.

With respect to timing, managed honey bee colonies should be introduced into the orchard when approximately five percent of the apple blossoms have opened (i.e. the king blossoms – the primary or central bud within a cluster that opens first) (Delaplane and Mayer, 2000). If the hives are placed in orchards too early, that is before the king blossoms open, bees may use alternative, as in non-crop, flowering plants. It is likely that the bees will return to the apple flowers when they open, because of their overall abundance and quality as a food plant, though early release of honey bees could, nonetheless, cause a minor diversion of pollination services away from the target apple flowers.

Honey bee foraging behaviour typically involves flower/floral constancy, which is when pollinating insects concentrate their flower visits to the same plant species for pollen collection, despite there being other available forage resources (Waser, 1986; Waser and Ollerton, 2006; Chittka *et al.*, 1999). It is thought that competition for pollinators may occur when there is a high abundance of many alternative floral resources with overlapping flowering periods in or near apple orchards. It has been shown, for instance, that honey bees may forage on ground cover, for example dandelion (*Taraxacum officinale*) and white clover (*Trifolium repens*), rather than apple flowers (Free, 1968, 1993; Mayer and Lunden, 1991; MacRae *et al.*, 2009).

An additional management option, therefore, which is often recommended or practiced, is to remove ground flora that is flowering in synchrony with apple (Abrol, 2011). However, it is not always clear if this practice actually increases apple pollination. It is most likely that honey bee colonies continue to forage for apple pollen, regardless of the presence of co-flowering dandelion (Laverty and Hiemstra, 1998). There may be other negative consequences of removing dandelion and other non-crop flowering plants. During times when apple is not blooming, these alternative forage resources are extremely valuable for wild resident bees (Free, 1993; MacRae *et al*., 2005; Vaughan *et al*., 2007; Sheffield *et al*., 2008a, 2008b; Potts *et al*., 2010), many of which may also be important native apple pollinators. The management of wild bees within apple orchards is discussed in more detail below.

Managed honey bee hives should be placed in a slightly elevated position, not directly on the ground, and where there is ample sunlight. The entrance should be shielded from direct wind and be clear of blockage or obstruction such as branches or tree trunks, with a direct line to forage resources. The hive entrance should therefore face either into the centre of the orchard or down rows of apple trees. As discussed above, bees will more likely forage down a row than across rows (Free, 1966).

It is important that overall hive placement should not be in long rows, as this leads to drifting and non-uniform colony strength. There are many approaches with respect to hive placement within an orchard. For example, in very large orchards with lots of apple flowers, honey bees may have shorter foraging ranges because of the abundant availability of food. Colonies, therefore, should be dispersed throughout the orchard to provide uniform pollination coverage, and/or they should be placed away from the orchard/farm edges and concentrated towards the centre of the orchard.

In almond orchards, for example, concentrating managed honey bee hives towards the centre of the orchard increases foraging competition, which in turn forces a more uniform distribution of pollination throughout the orchard as bees try to reduce crowding or foraging on the same central cluster of trees (Loper *et al*., 1985). Hive placement strategy should also take into consideration the accessibility of vehicles to hives and machinery paths within orchards. Other orchardists prefer an irregular layout of managed hives – spread out, spaced apart and facing in different directions.

Stocking rates and competition

The decision to bring in managed honey bees to ensure adequate levels of pollination during apple bloom is always up to the farmer, and is usually based on trade-offs between inputs (financial) and outputs (yield), and the known physical (e.g. size) and biological attributes (e.g. native pollinator abundance and diversity, yield in previous years) of the orchard and surrounding habitats.

In some cases, wild bee pollination alone may provide sufficient pollination to meet the requirements of apple (Mallinger and Gratton, 2015), especially on smaller farms with suitable surrounding habitat. A recent study (Mallinger and Gratton, 2015) examined the effect of honey bees and wild bees on apple fruit set and found that neither the addition of managed honey bee hives, nor the increase in honey bee abundance (density) increased apple fruit set, suggesting that wild bees were sufficient for pollination needs in these orchards.

In apple orchards close to large forest fragments, wild flower patches or natural hedgerows with a diverse and abundant wild bee fauna, the addition of managed honey bee hives during apple bloom may not necessary. These findings highlight the importance of monitoring both bee diversity and abundance within orchards (FAO, 2016), and correlating this with fruit set/ yield and fruit quality statistics. Lower than expected, or greatly fluctuating yearly yield or fruit quality is indicative of poor pollination, and supplemental pollination by managed pollinators may be required.

Nonetheless, and in particular for large-scale apple production, farmers can choose to rent hives to ensure that optimum pollination takes place. For apple pollination with honey bee colonies, recommendations for stocking rates range between two to four full strength hives/ha for moderate levels of pollination (Delaplane and Mayer, 2000). Higher stocking rate recommendations (see Abrol, 2011) may lead to higher pollination rates, but also means higher production costs, such as for rental fees. In countries where *Apis cerana* colonies may be used instead of *A. mellifera*, especially in parts of Asia (Kumar, 1997), the stocking rate recommendations are much higher for example from 10 to 12 colonies/ha, as colonies of this species are typically smaller (Abrol, 2011).

5.2 LANDSCAPE MANAGEMENT

The general approaches to managing landscapes, with respect to managed honey bees, differs depending on if honey bee hives are rented or if they are raised or kept in the apple orchard.

The previous two sections outline general guidelines and strategies related to the use of managed honey bee hives for apple pollination. In this section, landscape management strategies are discussed that ensure hive owners keep strong honey bee colonies in the orchard over the long term, while simultaneously encouraging natural wild bee populations within and around the apple orchard.

Conservation of wild bee fauna

Wild bees play an important and direct role in the pollination of many crops, and in some cases, even more so than introduced, managed honey bees (Vicens and Bosch, 2000; Bosch and Kemp, 2001; Vaughan *et al.*, 2007; Breeze *et al.*, 2011; Garibaldi *et al.*, 2011, 2013; Földesi *et al.*, 2015; Mallinger and Gratton, 2015; Russo *et al.*, 2015). In order to maintain high wild bee diversity, the apple orchard and surrounding habitat, should be rich in plants that provide ample floral resources such as nectar and pollen, and have sufficient and diverse nesting substrates, for example exposed bare soils, fallen logs and uncut plant stems (See Greenleaf and Kremen, 2006a; Garibaldi *et al.*, 2011; Sheffield *et al.*, 2013). The former is also important for honey bees when apiaries are maintained adjacent to orchards, especially when wild honey bees are part of the local bee fauna. Highly social species, such as honey bees, require food inputs throughout the growing season, so sites rich in crops and wild plants that flower sequentially are best suited to maintaining bee populations.

Wild bees may also play an indirect role in increasing pollination services to apples. The presence of wild bees within apple orchards may affect honey bee foraging behaviour by increasing the rates of honey bee movement, thus resulting in increased pollen deposition and fruit set in apples, as recently demonstrated in sunflower crop systems (Greenleaf and Kremen, 2006b). Since apple orchards are more dependent on the movement of pollinators between apple

© M.P.Garratt

trees and pollenizer trees, studies might investigate whether or not the presence or increase of wild bees does, in fact, increase the movement and activity of honey bees in apple orchards, thus resulting in more successful fruit production (James and Pitts-Singer, 2008).

Approaches to maintaining and encouraging wild bees all year-round

The honey bees *A. mellifera* and *A. cerana* are both effective apple pollinators (Verma and Dulta, 1986; Kumar, 1997; Stern *et al.*, 2001) and, in their respective ranges or areas of use, are often found to be the most frequent visitors to apple flowers (Joshi and Joshi, 2010). There are, however, other wild bees that are effective apple pollinators, including bumble bees (*Bombus*), mining bees (*Colletes, Andrena*), carpenter bees (*Xylocopa, Ceratina*) and sweat bees (*Lasioglossum, Halictus, Augochlora*) (Kendall, 1973; Kendall and Solomon, 1973; Dashad and Sharma, 1994; Thomson and Goodell, 2001; Park *et al.*, 2010; 2012; Adamson *et al.*, 2012). In fact, a few studies report mining bees of the genus *Andrena* as being the most frequent and common apple flower visitor (Adamson *et al.*, 2012; Gardner and Ascher, 2006). An additional and important group of wild apple pollinators are the mason bees (*Osmia*), and a few species are managed for this purpose, particularly *O. cornifrons*, *O. cornuta* (Old World) and *O. lignaria* (North America).

Mason bees are mostly polylectic (Bosch and Kemp, 2002), but these species have a strong preference for foraging on fruit trees, including apple. Mason bees are solitary, and normally nest in hollow stems and reeds, or previously excavated holes in trees as in tubular cavities (Michener, 2007). Their common name relates to the fact that they normally construct individual nesting cell partitions for each one of their individually laid eggs using mud, or other pliable materials, including masticated leaves. Mason bees are effective and efficient apple pollinators that are normally active during the early spring, corresponding to the apple flowering period (Park *et al.*, 2012). When visiting apple flowers, they directly contact the stigmas of the flower blossom with the pollen-laden scopa on their abdomens. Finally, mason bees are easily managed or promoted for growers to maintain (see Maeta, 1990).

Several mason bee species have been shown to be more effective than honey bees at pollinating apples (see Torchio, 1985; Ladurner *et al.*, 2004; Garratt *et al.*, 2014). For example, pollination services for 1 acre (0.4 ha) of apple orchard can be fully pollinated by 250 to 500 female *Osmia cornifrons*, compared to 50 000 honey bees, based on the individual visitation rates of each species. An individual *O. cornifrons* will visit 15 flowers per minute, which equals 2 450 apple flowers/day, compared to an individual honey bee, which may visit 50 flowers per day (Biddinger *et al.*, 2013).

Similarly, *O. lignaria*, the Blue Orchard Bee of North America is frequently used for apple pollination (Richards and Kevan, 2002; Sheffield, 2014) and, in Japan, *O. cornifrons* (Japanese Orchard Bee) is used to pollinate over 80 percent of apples grown in that country. As a result of the success of this pollinator of apple crops, *O. cornifrons* was introduced to the United States (Maryland) circa 1976 to pollinate apples (Batra, 1979).

Encouraging and managing *Osmia* pollinators

It is known that bee populations need floral resources such as nectar and pollen and nesting substrate to thrive. It is also known that most *Osmia* spp. naturally nest in hollow stems and reeds or previously excavated holes in trees (see above). It is recommended that apple orchardists evaluate the size of their farm, around the edge and surrounding habitat from the centre of the farm. If the apple farm is small (<1 ha) and surrounded by wooded areas, this is probably enough to support small *Osmia* populations that are important for apple pollination. If the farm is sufficiently large, with little nesting substrate for *Osmia* bees on the farm, the creation of small wooded areas or plots in an apple orchard might be enough to house *Osmia* bees, though nesting sites can be supplemented by creating artificial nests (Sheffield *et al.*, 2008a; Gruber *et al.*, 2011).

Floral resources in apple orchards

Planting floral resources on an apple farm so that they do not compete with blooming apple flowers, before or after apple bloom, could improve the reproductive fitness and success of *Osmia* and other social and solitary bee populations that will directly and indirectly positively affect apple pollination (Sheffield *et al.*, 2008b; Garratt *et al.*, 2014). During apple flowering it is beneficial to have both honey bees and wild bees within the orchard as pollinators, and it has been shown in other crop systems that the presence of wild bees (including *Osmia*) can affect honey bee foraging patterns in such a way as to increase the rate of their movement, pollen deposition and pollination services (Greenleaf and Kremen, 2006b). This may also apply to honey bee foraging behaviour in apple orchards and could be an important factor in the resulting successful apple production, since increased honey bee movement and visitations between apple trees and pollenizers (i.e. cultivars) is critical.

Bee-friendly habitats for maintaining pollinator communities

Important components of building and maintaining bee-friendly habitats include ensuring: abundant and diverse nectar and pollen resources (i.e. food plants); water; and suitable nesting habitats and/or suitable nesting materials are available (Figure 12).

Box 1

TIPS FOR ENSURING PLANT DIVERSITY.

- Less mowing and removal of naturally occurring plants along the edges of the orchard will promote wild floral patches to occur. This requires no additional labour.
- Allow weedy species, or herbaceous ground cover, to grow within the orchard when apple is not in bloom. These plants provide an important source of food for pollinators for 'off-apple bloom season' periods.
- Plant flowering species adjacent to, or within, the apple orchard, as these provide essential resources for native bees and other beneficial organisms. Preferably use local native species. To avoid competition, these plant species should bloom at a different time to the target crop, in this case, apple.
- Creating a flower strip or patch (minimum 1m in diameter or more is ideal) with a diversity of plants having a range of flower colours is helpful to pollinators. Bees are especially attracted to blue, white and yellow flowers.

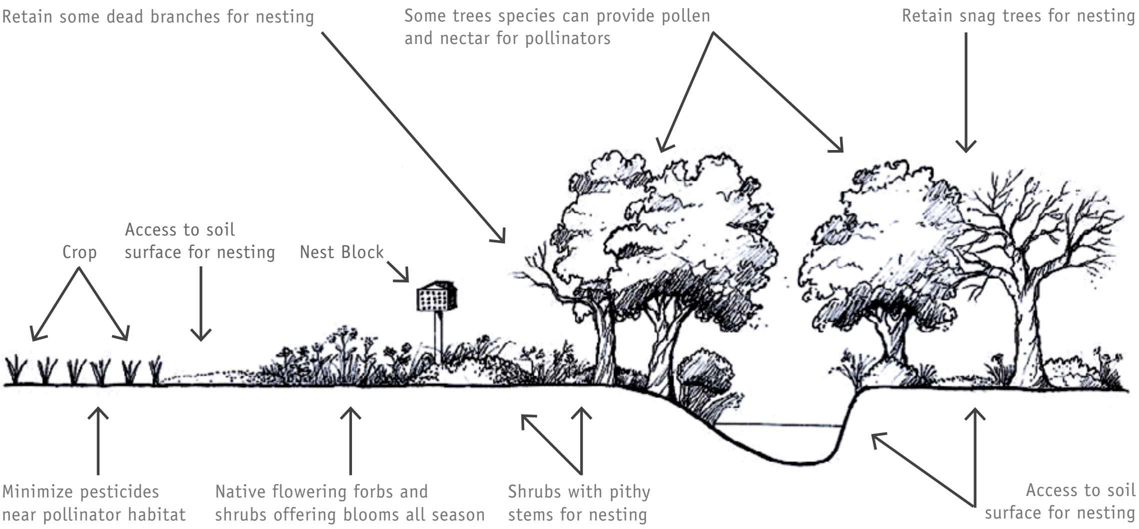
Nectar and pollen resources. A diversity of plant species that flower at different times throughout the season, while producing nectar and pollen, will ensure that food resources are not limited or lacking for any pollinators that might be present at various times of the year in a given orchard. This is especially important when apple is not in bloom. Bee populations, in general, need food from early spring until the autumn.

Water resources. Most pollinators, including bees, need access to water, though most is obtained from nectar (Willmer 1986, 1988). To encourage bees to persist within the farm, providing easy access to water, either directly or through wet sand or pebbles is important. Water sources can be natural or provided in shallow containers. These water containers can have pebbles, rocks or other components to serve as landing areas so that pollinators such as insects do not drown in the container. Water is important for honey bees for cooling their hive in hot weather (Ohguchi and Aoki, 1983) but is also important for solitary bees that cannot find sufficient water in the nectar collected (Michener, 1974; Willmer, 1986; 1988). In addition, other bee species such as some mason bees, need water, specifically that found in mud, to assist in nest building.

Suitable nesting habitats and materials. Habitat diversity within a farm can create suitable natural nesting habitats for a diversity of bees. For example leaving dead trees, branches or fallen logs that have dead stems or holes can be ideal for some solitary stem-nesting bees. In addition, leaving patches of bare, or sparsely vegetated, soil in an orchard would encourage many types of ground-nesting bees. Ground nesting bees prefer loose, well-drained soils in order to dig nests. After ground-nesting bees have established, avoid compacting or turning the soil.

Figure 12

ENHANCING NESTING SITES FOR NATIVE BEE CROP POLLINATORS.



Source: USDA AF Note - 34 2007

There are plenty of options for establishing artificial nests for encouraging solitary wild bees in orchards. Examples are nest blocks or 'bee condos' that are easy to build, and some types are sold commercially. To encourage stem-nesting bees it is common to provide artificial nests in the form of bundled hollow or pithy stems. These nest blocks often attract apple-pollinating bees, such as the blue orchard bees mentioned above.

These nest boxes, or bundled hollow stems, often vary in diameter so as to attract a diversity of bees (or wasps). Both nest boxes and stem bundles could be hung outside, under a natural or constructed shelter, usually above the vegetation, 1 to 2 m off the ground, and faced in the direction of the rising sun. During the colder months these artificial nest boxes and stem bundles can be placed in a shed or a protected area.

Many bees nest in the ground, therefore it is recommended that patches of bare soil or sparsely vegetated patches are left on a farm or in an orchard. Potential nesting habitat for ground-nesters can be created artificially by using soil-filled planters.

Conclusion

Clearly, ecosystem services are essential to human life, including pollination that supports food production. Many factors act on different scales, and affect land use and management practices that can sustain or encourage pollination services and, in turn, improve food production systems.

On the local scale, farmers are the decision makers. To encourage pollinator-friendly agricultural and land management decisions and practices, information should be available and readily accessible to farmers. This Manual has consolidated information about pollinators and the best practices specific to bees and apple production (Box 2).

Box 2

SUMMARY ACTIONS FOR OPTIMIZING POLLINATION WITHIN APPLE ORCHARDS.

1. Know your pollinators – both wild and managed. Important points to consider:
   a. Managed bees (normally honey bees): i) time of introduction; ii) hive placement; iii) stocking rates; and iv) colony hygiene.
   b. Wild bees: i) create and/or introduce suitable nesting habitat (natural or artificial); and ii) alternative food resources (outside apple bloom times), know their floral/food requirements.
2. Know your alternative food resources (non-crop trees and plants) – ensure resources are available year-round and outside major apple bloom times and within proximity to the apple orchard.
3. Know your nesting resources – natural and artificial.
4. Avoid or limit the use of agricultural chemicals (herbicides, fungicides, and pesticides). If use is necessary, consider: adhering to the label in terms of concentration, frequency, and timing of application.
5. Consider orchard structure – important points to consider: i) mixing compatible apple cultivars which co-flower along with good pollenizer cultivars; ii) placement of pollenizers; and iii) spacing of apple/pollenizer trees and synchronicity.

REFERENCES

Abbott, V.A., Nadeau, J.L., Higo, H.A. & Winston, M.L. 2008. Lethal and sublethal effects of imidacloprid on *Osmia lignaria* and clothianidin on *Megachile rotundata* (Hymenoptera: Megachilidae). *J. Econ. Entomol.*, 101(3): 784-796.

Abel, C.A. & Wilson, R.L. 1998. The use of diverse plant species for increasing *Osmia cornifrons* (Hymenoptera: Megachilidae) in field cages. *J. Kansas Entomol. Soc.*, 71: 23–28.

Abrol, D.P. 1993. Insect pollination and crop production in Jammu and Kashmir. *Current Science*, 65(3): 265-269.

Abrol, D. P. 2011. *Pollination biology: biodiversity conservation and agricultural production*. New York, Springer.

Abrol, D.P. 2012. *Pollination biology: biodiversity conservation and agricultural production*. Berlin, Germany, Springer Science & Business Media. 792 pp.

Adamson, N.L., Roulston, T.H., Fell, R.D. & Mullins, D.E. 2012. From April to August—wild bees pollinating crops through the growing season in Virginia, USA. *Environ. Entomol.*, 41(4): 813-821.

Alexander, B.A. 1991. A cladistic analysis of the genus *Apis*. In D.R. Smith, ed. *Diversity of the genus Apis*, pp. 1-28. Boulder, CO, Westview Press. 265 pp.

Anvari, S.F. & Stösser, R. 1981. Über das Pollenschlauchswachstum beim Apfel. *Mitteilungen Klosterneuberg*, 31: 24–30.

Aziz, M., Jadoon, S. & Ziviqar, S. 2013. Apples pulp (*Pyrus malus*) nutritional profiling evaluation of various varieties of Balochistan. *Pakistan J. Nutrition*, 12(3): 239-243.

Batra, S.W.T. 1967. Crop pollination and the flower relationships of the wild bees of Ludhiana, India (Hymenopterea: Apoidea). *J. Kansas Entomol. Soc.*, 40(2): 164-177.

Batra, S.W.T. 1979. *Osmia cornifrons* and *Pithitis smaragdula*, two Asian bees introduced into the United States for crop pollination. *Proc. IVth Int. Symp. On pollination, Md. Agric. Exp. Sta. Spec. Misc. Publ.* 1: 307-312.

Batra, S.W.T. 1996. Biology of *Apis laborios* Smith, a pollinator of apples at high altitude in the Great Himalaya Range of Garhwal, India, (Hymenoptera: Apidae). *J. Kansas Entomol. Soc.*, 69(2): 177-181.

Barthélémy, C. 2012. Nest trapping, a simple method for gathering information on life histories of solitary bees and wasps. Bionomics of 21 species of solitary aculeate in Hong Kong. *Hong Kong Entomol. Bull*, 4(1): 3-37.

Biddinger, D.J., Robertson, J.L., Mullin, C., Frazier, J., Ashcraft, S.A., Rajotte, E.G.,Joshi, N.K. & Vaughn, M. 2013. Comparative toxicities and synergism of apple orchard pesticides to *Apis mellifera* (L.) and *Osmia cornifrons* (Radoszkowski). *PloS ONE*, 8(9), e72587.

Blaauw, B.R. & Isaacs, R. 2012. Larger wildflower plantings increase natural enemy density, diversity, and biological control of sentinel prey, without increasing herbivore density. *Ecol. Entomol.*, 37(5): 386-394.

Blaauw, B.R. & Isaacs, R. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *J. Appl. Ecol.*, 51(4), 890-898.

Blacquiere, T., Smagghe, G., Van Gestel, C.A. & Mommaerts, V. 2012. Neonicotinoids in bees: a review on concentrations, side-effects and risk assessment. *Ecotoxicology*, 21(4), 973-992.

Bosch, J. & Kemp, W.P. 2001. *How to manage the Blue Orchard Bee as an orchard pollinator.* Sustainable Agriculture Network Handbook Series. Book No 5.

Bosch, J. & Kemp, W.P. 2002. Developing and establishing bee species as crop pollinators: the example of *Osmia* spp. (Hymenoptera: Megachilidae). *Bull. Entomol. Res.*, 92: 3-16.

Brain, P. & Landsberg, J.J. 1981. Pollination, initial fruit set and fruit drop in apples: analysis using mathematical models. *J. Hort. Sci.*, 56:41–54.

Brault, A. & de Oliveira, D. 1995. Seed number and an asymmetry index of 'McIntosh' apples. *HortScience*, 30: 44–46.

Breeze, T.D., Bailey, A.P., Balcombe, K. G. & Potts, S.G. 2011. Pollination services in the UK: How important are honeybees? *Agricult. Ecosystems & Environ.*, 142(3): 137-143.

Brittain, W.H. 1933. Apple pollination studies in the Annapolis Valley, Nova Scotia. Canadian Department of Agriculture Bulletin, New Series 162: 1–198.

Brittain, W.H. & Eidt, C.C. 1933. Seed content, seedling production and fruitfulness in apples. *Can. J. Res.* 9: 307–333.

Brittain, C. & Potts, S.G. 2011. The potential impacts of insecticides on the life-history traits of bees and the consequences for pollination. *Basic and Applied Ecology*, 12(4), 321-331.

Brown, S. 2012. Apple. In M.L. Badenes & D.H. Byrne, eds. *Fruit breeding*, pp. 329-367. Berlin, Germany, Springer Science & Business Media.

Bultitude, J. 1983. *Apples. A guide to the identification of international varieties*. London, UK, Macmillan Press.

Canadian Food and Inspection Agency. No date. The Biology of *Malus domestica* Borkh. (Apple), Canadian Food Inspection Agency, (Available at: http://www.inspection.gc.ca/plants/plants-with-novel-traits/applicants/directive-94-08/biology-documents/malus-domestica/eng/1404417088821/1404417158789?chap=3). Accessed December 2015.

Cane, J.H. 1991. Soils of ground-nesting bees (Hymenoptera: Apoidea): texture, moisture, cell depth and climate. *J. Kansas Entomol. Soc.*, 64: 406-413.

Cane, J.H. 2008. A native ground-nesting bee (*Nomia melanderi*) sustainably managed to pollinate alfalfa across an intensively agricultural landscape. *Apidologie*, 39(3): 315-323.

Carr, S.G.M. & Carr, D.J. 1961. The functional significance of syncarpy. *Phytomorphology*, 11: 249–256.

Carvalheiro, L.G., Seymour, C.L., Veldtman, R. & Nicolson, S.W. 2010. Pollination services decline with distance from natural habitat even in biodiversity-rich areas. *J. App. Ecol.*, 47: 810–820.

Childers, N.F. 1983. *Modern fruit science*, Ninth Edition. Gainesville, FL, Horticultural Publications.

Chittka, L., Thomson, J.D. & Waser, N.M. 1999. Flower constancy, insect psychology, and plant evolution. *Naturwissenschaften*, 86(8): 361-377.

Cornille, A., Gladieux, P., Smulders, M.J., Roldán-Ruiz, I., Laurens, F., Le Cam, B., Nersesyan, A., Clavel, J., Olonova, M., Feugey, L., Gabrielyan, I., Zhang, X., Tenaillon, M.I. & Giraud, T. 2012. New insight into the history of domesticated apple: secondary contribution of the European wild apple to the genome of cultivated varieties. *PLoS Genetics*, 8(5), e1002703.

Crane, E. 1999. *The world history of beekeeping and honey hunting*. London, UK, Duckworth.

Cresti, M., Ciampolini, F. & Sansavini, S. 1980. Ultrastructure and histochemical features of pistil of *Malus communis*: the stylar transmitting tissue. *Scientia Horticulturae*, 12: 327–337.

Cripps, C. & Rust, R.W. 1989a. Pollen preferences of seven *Osmia* species (Hymenoptera: Megachilidae). *Environ. Entomol.*, 18(1): 133-138.

Cripps, C. & Rust, R.W. 1989b. Pollen foraging in a community of *Osmia* bees (Hymenoptera: Megachilidae). *Environ. Entomol.*, 18(4): 582-589.

Cross, J.V. & Dickler, E. eds. 1994. Guidelines for integrated production of pome fruits in Europe: IOBC Technical Guideline III. *IOBC/WPRS Bulletin*, 17(9): 1–8.

Dashad, S.S. & Sharma, J.K. 1994. Insect visitors of apple (*Malus domestica*) flowers in mid-hills of Himachal Pradesh. Indian *J. Agricult. Sciences*, 647: 514-515.

Degrandi-Hoffman, G., Hoopingarner, R. & Baker, K.K. 1985. The influence of honey bee 'sideworking' behavior on cross-pollination and fruit set in apples. *HortScience*, 20: 397–399.

Delaplane, K.S. & Mayer, D.F. 2000. *Crop pollination by bees*. New York, NY, CABI Publishing.

Dulta, P.C. & Verma, L.R. 1987. Role of insect pollinators on yield and quality of apple fruit. *Indian J. Hort.*, 44(3): 274-279.

Ekroos, J., Olsson, O., Rundlöf, M., Wätzold, F. & Smith, H.G. 2014. Optimizing agri-environment schemes for biodiversity, ecosystem services or both? *Biol. Conserv.*, 172, 65-71.

Elzebroek, A.T.G. & Wind, K. 2008. *Guide to cultivated plants*. Wallingford, UK, CAB International.

Endress, P.K. 1994. *Diversity and evolutionary biology of tropical flowers*. Cambridge, UK, Cambridge University Press.

Evans, E., Burns, I., & Spivak, M. 2007. *Befriending bumble bees: a practical guide to raising local bumble bees*. University of Minnesota Extension.

Evans, K.M., Patocchi, A., Rezzonico, F., Mathis, F., Durel, C.E., Fernández-Fernández, F., Boudichevskaia, A., Dunemann, F., Stankiewicz-Kosyl, M., Gianfranceschi, L., Komjanc, M., Lateur, M., Madduri, M., Noordijk, Y. & van de Weg, W. E. 2011. Genotyping of pedigreed apple breeding material with a genome-covering set of SSRs: trueness-to-type of cultivars and their parentages. *Mol. Breeding*, 28(4), 535-547.

FAO. 2016. *Protocol to detect and monitor pollinator communities: Guidance for practitioners*. (Available at: http://www.fao.org/pollination/resources/en).

FAOSTAT. 2015. Top production world (available at: http://faostat.fao.org/site/339/default.aspx). Accessed 12 December 2015.

Faust, M. 1989. *Physiology of temperate zone fruit trees*. New York, NY, John Wiley and Sons.

Ferree, D.C., Bishop, B.L., Schupp, J.R., Tustin, D.S. & Cashmore, W.M. 2001. Influence of flower type, position in the cluster and spur characteristics on fruit set and growth of apple cultivars. *J. Hort. Sci. Biotech*., 76:1–8.

Földesi, R., Kovács-Hostyánszki, A., Kőrösi, Á., Somay, L., Elek, Z., Markó, V., Sárospataki, M., Bakos, R., Varga, A., Nyisztor, K. & Báldi, A. 2015. Relationships between wild bees, hoverflies and pollination success in apple orchards with different landscape contexts. *Agricultural and Forest Entomology*, DOI: 10.1111/afe.12135

Free, J.B. 1966. The foraging areas of honeybees in an orchard of standard apple trees. *J. Appl. Ecol*., 3(2): 261-268.

Free, J.B. 1968. Dandelion as a competitor to fruit trees for bee visits. *J. Appl. Ecol*. 5: 169-178.

Free, J.B. 1993. *Insect pollination of crops,* Second Edition. San Diego, CA, Academic Press.

Fye, R.E. & Medler, J.T. 1954. Field domiciles for bumblebees. *J. Econ. Entomol*., 47: 672-6.

Ganie, M.A., Pal, A.K. & Ahmad, N. 2013. Native insect pollinators in apple orchards under different management practices in the Kashmir Valley. *Turkish Journal of Agriculture – Food Science and Technology*, 1(1): 29-36.

Gardner, K.E. & Ascher, J.S. 2006. Notes on the native bee pollinators in New York apple orchards. *J. New York Entomol. Soc*., 114(1): 86-91.

Garibaldi, L.A., Steffan-Dewenter, I., Kremen, C., Morales, J.M., Bommarco, R., Cunningham, S.A., Carvalheiro, L.G., Chacoff, N.P., Dudenhöffer, J.H., Greenleaf, S.S., Holzschuh, A., Isaacs, R., Krewenka, K., Mandelik, Y., Mayfield, M.M., Morandin, L.A., Potts, S.G., Ricketts, T.H., Szentgyörgyi, H., Viana, B.F., Westphal, C., Winfree, R. & Klein, A.M. 2011. Stability of pollination services decreases with isolation from natural areas despite honey bee visits. *Ecol. Letters*, 14(10): 1062-1072.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhöffer, J.H., Freitas, B.M., Ghazoul, J., Greenleaf, S., Hipólito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, K.M., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlöf, M., Seymour, C.L., Schüepp, C., Szentgyörgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., Westphal, C., Williams, N. & Klein, A.M. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, 339(6127): 1608-1611.

Garratt, M.P.D., Breeze, T.D., Jenner, N., Polce, C., Biesmeijer, J.C. & Potts, S.G. 2014. Avoiding a bad apple: Insect pollination enhances fruit quality and economic value. *Agricult. Ecosyst. & Environ*., 184: 34-40.

FAO. 2014. *Pollinator safety in agriculture*, Roubik, D.W. ed. (Available from the Website: http://www.fao.org/pollination/resources, publication http://www.fao.org/3/a-i3800e.pdf).

Gradish, A.E., Scott-Dupree, C.D. & Cutler, G.C. 2012a. Susceptibility of *Megachile rotundata* to insecticides used in wild blueberry production in Atlantic Canada. *J. Pest Science*, 85(1): 133-140.

Gradish, A.E., Scott-Dupree, C.D., Frewin, A.J. & Cutler, G.C. 2012b. Lethal and sublethal effects of some insecticides recommended for wild blueberry on the pollinator *Bombus impatiens. Can. Ent.*, 144(03): 478-486.

Greenleaf, S.S. & Kremen, C. 2006a. Wild bee species increase tomato production and respond differently to surrounding land use in Northern California. *Biol. Conserv.*, 133(1): 81-87.

Greenleaf, S.S. & Kremen, C. 2006b. Wild bees enhance honey bees' pollination of hybrid sunflower. *PNAS*, 103(37), 13890-13895.

Gruber, B., Eckel, K., Everaars, J., & Dormann, C. F. 2011. On managing the red mason bee (*Osmia bicornis*) in apple orchards. *Apidologie*, 42(5): 564-576.

Gupta, J.K., Goyal, N.P., Sharma, J.P. & Gautam, D.R. 1993. The effect of placement of varying numbers of *Apis mellifera* colonies on the fruit set in apple orchards having different proportions of pollinisers. *In* G.K. Veeresh, R. Uma Shankar & K.N. Ganeshaiah, eds. *Proceedings of the international symposium on pollination in the tropics*, pp. 197-201. India, International Union for Studies on Social Insects.

Hancock, J.F., Luby, J.J., Brown, S.K. & Lobos, G.A. 2008. Apples. In J.F. Hancock, ed. *Temperate fruit crop breeding: germplasm to genomics*, pp. 1-37. Berlin, Germany, Springer Science & Business Media. 455 pp.

Hannon, L.E. & Sisk, T.D. 2009. Hedgerows in an agri-natural landscape: potential habitat value for native bees. *Biol. Conserv.*, 142(10); 2140-2154.

Harris, S.A., Robinson, J.P. & Juniper, B.E. 2002. Genetic clues to the origin of the apple. *TRENDS in Genetics*, 18(8), 426-430.

Heard, T.A. 1999. The role of stingless bees in crop pollination. *Ann. Rev. Entomol.*, 44(1), 183-206.

Henry, M., Beguin, M., Requier, F., Rollin, O., Odoux, J.F., Aupinel, P., Aptel, J., Tchamitchian, S. & Decourtye, A. 2012. A common pesticide decreases foraging success and survival in honey bees. *Science*, 336(6079): 348-350.

Hobbs, G.A., Nummi, W.O. & Virostek, J.F. 1962. Managing colonies of bumble bees (Hymenoptera: Apidae) for pollination purposes. *Can. Ent.* 94(11): 1121-1132.

Hokanson, S.C., McFerson, J.R., Forsline, P.L., Lamboy, W.F., Luby, J.J., Djangaliev, A.D. & Aldwinckle, H.S. 1997. Collecting and managing wild *Malus* germplasm in its center of diversity. *HortScience*, 32(2), 173-176.

Isaacs, R., Tuell, J., Fiedler, A., Gardiner, M. & Landis, D. 2008. Maximizing arthropod-mediated ecosystem services in agricultural landscapes: the role of native plants. *Frontiers in Ecology and the Environment*, 7(4), 196-203.

James, R. & Pitts-Singer, T.L. eds. 2008. *Bee pollination in agricultural ecosystems*. Oxford, UK, Oxford University Press.

Jana, B.R. 2001. Effect of self and cross pollination on the fruit set behaviour of some promising apple genotypes. *J. Appl. Hort.*, 3(1): 51-52

Javorek, S.K., Mackenzie, K.E. & Vander Kloet, S.P. 2002. Comparative pollination effectiveness among bees (Hymenoptera: Apoidea) on lowbush blueberry (Ericaceae: *Vaccinium angustifolium*). *Ann. Entomol. Soc. Amer.*, 95(3): 345-351.

Joshi, N.C. & Joshi, P.C. 2010. Foraging behaviour of *Apis* spp. on apple flowers in a subtropical environment. *New York Science Journal*, 3(3): 71-76.

Kakar, K.L. 2000. Effect of pollination strategies on fruit set of apple in Himanchal Pradesh. *In* M. Matsuka, L. R. Verma, S. Wongsiri, K. K. Shrestha, and U. Partap, eds. *Asian bees and beekeeping: progress of research and development. Proceedings of the Fourth Asian Apicultural Association International Conference, Kathmandu, Nepal, 23-28 March 1998*. pp 166-168. Kathmandu, Nepal. 274 pp.

Kearns C.A. & Thomson J.D. 2001. *The natural history of bumblebees: a sourcebook for investigations*. USA, University Press of Colorado.

Kendall, D.A. 1973. The viability and compatibility of pollen on insects visiting apple blossom. *J. Appl. Ecol.*, 10(3): 847-853.

Kendall, D.A. & Solomon, M.E. 1973. Quantities of pollen on the bodies of insects visiting apple blossom. *J. Appl. Ecol.*, 10(2): 627-634.

Kendall, D.A. & Smith, B.D. 1975. The foraging behaviour of honeybees on ornamental *Malus* spp. used as pollinizers in apple orchards. *Journal of Applied Ecology*, 12(2): 465-471.

Keulemans, J., Brusselle, A., Eyssen, R., Vercammen, J. & Van Daele, G. 1996. Fruit weight in apple as influenced by seed number and pollinizer. *Acta Horticulturae*, 423: 201–210.

King, G.J., Alston, F.H., Battle, I., Chevreau, E., Gessler, C., Janse, J., Lindhout, P., Manganaris, A.G., Sansavini, S., Schmidt, H. & Tobutt, K. 1991. The 'European apple genome mapping Project' – developing a strategy for mapping genes coding for agronomic characters in tree species. *Euphytica*, 56(1): 89-94.

Korpela, E.L., Hyvönen, T., Lindgren, S. & Kuussaari, M. 2013. Can pollination services, species diversity and conservation be simultaneously promoted by sown wildflower strips on farmland? *Agricult. Ecosyst. & Environ.*, 179: 18-24.

Krombein, K.V. 1967. *Trap-nesting wasps and bees: life histories, nests, and associates*. Washington, DC, Smithsonian Institution Press,

Kron, P., Husband, B.C. & Kevan, P.G. 2001a. Across- and along-row pollen dispersal in high-density apple orchards: insights from allozyme markers. *J. Hort. Science Biotech.*, 76: 286–294.

Kron, P., Husband, B.C., Kevan, P.G. & Belaoussoff, S. 2001b. Factors affecting pollen dispersal in high-density apple orchards. *HortScience*, 36: 1039–1046.

Krupke, C.H., Hunt, G.J., Eitzer, B.D., Andino, G. & Given, K. 2012. Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One*, 7(1): e29268.

Kumar, L. 1997. Foraging ecology and behaviour of *Apis cerana* F. and *Apis mellifera* L. in pollinating apple and cherry flowers. Shimla, India, Himachal Pradesh University. (PhD Thesis)

Kwapong, P., Aidoo, K., Combey, R. & Karikari, A. 2010. *Stingless bees: importance, management and utilization. A training manual for stingless beekeeping*. Accra, Ghana North, Unimax Macmillan Ltd.

Landis, D.A., Menalled, F.D., Costamagna, A.C. & Wilkinson, T.K. 2005. Manipulating plant resources to enhance beneficial arthropods in agricultural landscapes. *Weed Science*, 53(6): 902-908.

Landis, D.A., Gardiner, M.M. & Tompkins, J. 2012. *Using native plant species to diversify agriculture. Biodiversity and insect pests: key issues for sustainable management*. Chichester, UK, Wiley, 276-92.

Ladurner, E., Recla, L., Wolf, M., Zelger, R. & Burgio, G. 2004. *Osmia cornuta* (Hymenoptera Megachilidae) densities required for apple pollination: a cage study. *J. Apicult. Res.*, 43(3): 118-122.

Ladurner, E., Bosch, J., Kemp, W.P. & Maini, S. 2005. Assessing delayed and acute toxicity of five formulated fungicides to *Osmia lignaria* Say and *Apis mellifera*. *Apidologie*, 36(3): 449.

Laverty, T. & Hiemstra, H. 1998. Effect of flowering dandelion as a competitor to flowers of fruit trees for pollen-collecting honey bees in Ontario. *Proceed. Entomol. Soc. Ontario*, 129: 3-8.

Lee, T.D. 1988. Patterns of fruit and seed production. *In* Doust JL, Doust LL, eds. *Plant reproductive ecology: patterns and strategies*. New York, Oxford University Press.

MacIvor, J.S., Cabral, J.M. & Packer, L. 2014. Pollen specialization by solitary bees in an urban landscape. *Urban Ecosystems*, 17(1): 139-147.

MacRae, A.W., Mitchem, W.E., Monks, D.W. & Parker, M.L. 2005. White clover (*Trifolium repens*) control and flower head suppression in apple orchards. *Weed Technology*, 19(2): 219-223.

MacRae, R., Martin, R. C., Juhasz, M. & Langer, J. 2009. Ten percent organic within 15 years: Policy and program initiatives to advance organic food and farming in Ontario, Canada. *Renewable Agriculture and Food Systems*. 24(2): 120-136

Maeta, Y. 1990. Utilization of wild bees. *Farming Japan*, 24: 13-19.

Mallinger, R.E. & Gratton, C. 2015. Species richness of wild bees, but not the use of managed honeybees, increases fruit set of a pollinator-dependent crop. *J. Appl. Ecol.*, 52(2): 323-330.

Mayer, D.F. & Johansen, C.A. 2003. The rise and decline of *Nomia melanderi* (Hymenoptera: Halictidae) as a commercial pollinator for alfalfa seed. In Strickler, K. & Cane, J.H. (eds). *For nonnative crops, whence pollinators of the future?* Lanham, Maryland, USA, Entomological Society of America.

Mayer, D.F. & Lunden, J.D. 1991. Honey bee foraging on dandelion and apple in apple orchards. *J. Entomol. Soc. British Columbia*, 88: 15-17.

McGregor, S.E. 1976. Insect pollination of cultivated crop plants. Agricultural Research Service, United States Department of Agriculture. Agriculture Handbook No. 496: 1–411.

Michener, C.D. 1974. *The social behavior of the bees: a comparative study*. Harvard University Press.

Michener, C.D. 2007. *The bees of the world*. Second Edition. Baltimore, USA, Johns Hopkins.

Miñarro, M. & Prida, E. 2013. Hedgerows surrounding organic apple orchards in north-west Spain: potential to conserve beneficial insects. *Agricult. Forest Entomol.*, 15(4): 382-390.

Morandin, L.A. & Kremen, C. 2013. Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecol. Applications*, 23(4): 829-839.

Morandin, L., Long, R., Pease, C. & Kremen, C. 2011. Hedgerows enhance beneficial insects on farms in California's Central Valley. *California Agriculture*, 65(4): 197-201.

Morgan, J. & Richards, A. 2002. *The new book of apples*. London: Ebury Press.

Moroń, D., Grześ, I.M., Skorka, P., Szentgyörgyi, H., Laskowski, R., Potts, S.G. & Woyciechowski, M. 2012. Abundance and diversity of wild bees along gradients of heavy metal pollution. *J. Appl. Ecol.*, 49(1): 118-125.

Moroń, D., Szentgyörgyi, H., Skórka, P., Potts, S.G. & Woyciechowski, M. 2014. Survival, reproduction and population growth of the bee pollinator, *Osmia rufa* (Hymenoptera: Megachilidae), along gradients of heavy metal pollution. *Insect Conserv. Diver.*, 7(2): 113-121.

Ohguchi, O. & Aoki, K. 1983. Effects of colony need for water on optimal food choice in honey bees. *Behav. Ecol. Sociobiol.*, 12(1): 77-84.

O'Toole, C. 2013. *Bees: A natural history*. Buffalo, New York, USA and Richmond Hill, Ontario, Canada, Firefly Books.

Papademetriou, M.K., Herath, E.M., George, A.P., Dorji, P. & Zailong, L. 1999. *Deciduous fruit production in Asia and the Pacific*. RAP Publication (FAO) Eng No. 1999/10.

Park, M.G., Orr, M.C., Danforth, B.N. & Hall, C. 2010. The role of native bees in apple pollination. *NY Fruit Quart.*, 18: 21-25.

Park, M., Danforth, B., Losey, J., Biddinger, D., Vaughan, M., Dollar, J., Rajotte, E. & Angello, A. 2012. *Wild pollinators of eastern apple orchards and how to conserve them*. Cornell University, Penn State University and The Xerces Society. (Available at: URL: http://www.northeastipm.org/park2012).

Partap, U. 2012. Honey bees in mountain agriculture. Leisa India. March 2012. Pp. 5-12.

Partap, U. & Partap, T. 2002. *Warning signals from the apple valleys of the Hindu Kush-Himalayas – Productivity concerns and pollination problems*. Shreshtha, A.B.M. ed, Kathmandu, Nepal, Centre for Integrated Mountain Development (ICIMOD).

Peck, G.M., Andrews, P.K., Reganold, J.P. & Fellman, J.K. 2006. Apple orchard productivity and fruit quality under organic, conventional, and integrated management. *HortScience*, 41(1): 99-107.

Peters, V.E., Carroll, C.R., Cooper, R.J., Greenberg, R. & Solis, M. 2013. The contribution of plant species with a steady-state flowering phenology to native bee conservation and bee pollination services. *Insect Conserv. Diver.*, 6(1): 45-56.

Pettis, J.S., Lichtenberg, E. M., Andree, M., Stitzinger, J., Rose, R. & D. vanEngelsdorp. 2013. Crop pollination exposes honey bees to pesticides which alters their susceptibility to the gut pathogen *Nosema ceranae. PLoS ONE*, 8(7): e70182. (Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0070182). Accessed 3 March 2016.

Pitts-Singer, T.L. & Cane, J.H. 2011. The alfalfa leafcutting bee, *Megachile rotundata*: the world's most intensively managed solitary bee. *Ann. Rev. Entomol.*, 56: 221-237.

Potts, S.G., Vulliamy, B., Dafni, A., Ne'eman, G. & Willmer, P. 2003. Linking bees and flowers: how do floral communities structure pollinator communities? *Ecology*, 84(10): 2628-2642.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W.E. 2010. Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.*, 25(6): 345-353.

Pratt, C. 1988. Apple flower and fruit: morphology and anatomy. *Horticultural Reviews* 10: 73–308.

Prokopy, R.J. 2003. Two decades of bottom-up, ecologically based pest management in a small commercial apple orchard in Massachusetts. *Agriculture, ecosystems & environment*, 94(3), 299-309.

Rader, R., Bartomeus, I., Garibaldi, L.A., Garratt, M.P.D., Howlett, B.G., Winfree, R., Cunningham, S.A., Mayfield, M.M., Arthur, A.D., Andersson, G.K.S., Bommarco, R., Brittain, C., Carvalheiro, L.G., Chacoff, N.P., Entling, M.H., Foully, B., Freitas, B.M., Gemmill-Herren, B., Ghazoul, J., Griffin, S.R., Gross, C.L., Herbertsson, L., Herzog, F., Hipólito, J., Jaggar, S., Jauker, F., Klein, A., Kleijn, D., Krishnan, S., Lemos, C.Q., Lindström, S.A.M, Mandelik, Y., Monteiro, V.M., Nelson, W., Nilsson, L., Pattemore, D.E., Pereirat, N.O., Pisanty, G., Potts, S.G., Reemer, M., Rundlöf, M., Sheffield, C.S., Scheper, J., Schüepp, C., Smith, H.G., Stanley, D.A., Stout, J.C., Szentgyörgyi, H., Taki, H., Vergara, C.H., Viana, B.F. & Woyciechowskinn, M. 2015. Non-bee insects are important contributors to global crop pollination. *PNAS*, (Web site: www.pnas.org/cgi/doi/10.1073/pnas.1517092112).

Raven, P.H., Evert, R.F. & Eichhorn, S.E. 1999. *Biology of plants*, Sixth Edition. New York, W.H. Freeman and Co.

Reganold, J.P., Glover, J.D., Andrews, P.K., & Hinman, H.R. 2001. Sustainability of three apple production systems. *Nature*, 410(6831): 926-930.

Richards, K.W. & Kevan, P.G. 2002. Aspects of bee biodiversity, crop pollination, and conservation in Canada. In Kevan P & Imperatriz Fonseca VL eds. - *Pollinating bees - The conservation link between agriculture and nature*. Ministry of Environment/Brasília. p.77-94.

Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M., Morandin, L.A., Ochieng, A. & Viana, B.F. 2008. Landscape effects on crop pollination services: are there general patterns? *Ecol. Letters*, 11: 499-515.

Robinson, T.L., Hoying, S., Sazo, M.M., DeMarree, A. & Dominguez, L. 2013. A vision for apple orchard systems of the future. *New York Fruit Quarterly*, 21(3): 11-16.

Robinson, W.S. 1979. Effects of apple cultivar on foraging behavior and pollen transfer by honey bees. *J. Amer. Soc. Hort. Sci*., 104: 596–598.

Russo, L., Park, M., Gibbs, J. & Danforth, B. 2015. The challenge of accurately documenting bee species richness in agroecosystems: bee diversity in eastern apple orchards. *Ecol. Evol.*, 5(17): 3531-3540.

Sansavini, S. 1997. Integrated fruit production in Europe: research and strategies for a sustainable industry. *Scientia Horticulturae*, 68(1): 25-36.

Saunders, M.E., Luck, G.W. & Mayfield, M.M. 2013. Almond orchards with living ground cover host more wild insect pollinators. *J. Insect Conserv*., 17(5), 1011-1025.

Schneider, D., Stern, R.A., Eisikowitch, D. & Goldway, M. 2002. The relationship between floral structure and honeybee pollination efficiency in 'Jonathan' and 'Topred' apple cultivars. *J. Hort. Science Biotech*., 77: 48–51.

Sedgley, M. 1990. Flowering of deciduous perennial fruit crops. *Hort. Rev*., 12: 223–264.

Sedgley, M. & Griffin, A.R. 1989. *Sexual reproduction of tree crops*. San Diego, CA, Academic Press.

Sharma, H.K., Gupta, J.K. & Thakur, J.R. 2004. Effect of bee pollination and polliniser proportion on apple productivity. *Acta Hort.*, 662: 451-454.

Sharma, H.K. & Gupta, J.K. 2001. Impact of bee pollination on sustainable production in apple orchards. *Pest Management and Economic Zoology*, 9: 45-48.

Sharma, G., Anand, R. & Sharma, O.C. 2006. Floral biology and effect of pollination in apple (*Malus x domestica*). *Indian J. Agricult. Sciences*, 75(10): 667-669.

Sharma, H.K., Partap, U., Bisht, K., Tewari, P. & Phartiyal, P. 2012. Impact of honeybee pollination in enhancing the apple production in Nainital district of Uttarakhand. *Advances in Pollen Spore Research*, 30: 99-102.

Sheffield, C.S. 2014. Pollination, seed set and fruit quality in apple: studies with *Osmia lignaria* (Hymenoptera: Megachilidae) in the Annapolis Valley, Nova Scotia, Canada. *J. Pollination Ecol.*, 12(13): 120-128.

Sheffield, C.S., Smith, R.F. & Kevan, P.G. 2005. Perfect syncarpy in apple (*Malus × domestica* 'Summerland McIntosh') and its implications for pollination, seed distribution and fruit production (Rosaceae: Maloideae). *Ann. Botany*, 95(4): 583-591.

Sheffield, C.S., Kevan, P.G., Westby, S.M. & Smith, R.F. 2008a. Diversity of cavity-nesting bees (Hymenoptera: Apoidea) within apple orchards and wild habitats in the Annapolis Valley, Nova Scotia, Canada. *Can. Entomol.*, 140(02), 235-249.

Sheffield, C. S., Westby, S. M., Smith, R. F., & Kevan, P. G. 2008b. Potential of bigleaf lupine for building and sustaining *Osmia lignaria* populations for pollination of apple. *The Canadian Entomologist*, 140(05), 589-599.

Sheffield, C.S., Kevan, P.G., Pindar, A. & Packer, L. 2013. Bee (Hymenoptera: Apoidea) diversity within apple orchards and old fields in the Annapolis Valley, Nova Scotia, Canada. *Can. Entomol.*, 145(01), 94-114.

Singh, V.P. and Misra, K.K. 2007. Pollination management in apple for sustainable production. *Progressive Horticulture*, 39(2): 139-148.

Stern, R.A., Eisikowitch, D. & Dag, A. 2001. Sequential introduction of honeybee colonies and doubling their density increases cross-pollination, fruit set and yield in Red Delicious' apple. *J. Hort. Science Biotech.*, 76(1): 17-23.

Stott, K.G. 1972. Pollen germination and pollen-tube characteristics in a range of apple cultivars. *J. Hort. Sci.*, 47:191–198.

Tasei, J.N., Carre, S., Bosio, P.G., Debray, P. & Hariot, J. 1987. Effects of the pyrethroid insecticide, WL85871 and phosalone on adults and progeny of the leaf-cutting bee *Megachile rotundata* F, pollinator of lucerne. *Pesticide Science*, 21(2): 119-128.

Thies, C. & Tscharntke, T. 1999. Landscape structure and biological control in agroecosystems. *Science*, 285(5429): 893-895.

Thomson, J.D. & Goodell, K. 2001. Pollen removal and deposition by honeybee and bumblebee visitors to apple and almond flowers. *J. Appl. Ecol.*, 38(5): 1032-1044.

Thorp, R.W. 2003. Bumble bees (Hymenoptera: Apidae): commercial use and environmental concerns. Pp. 21-40 In K. Strickler & J.H. Cane (eds.). *For nonnative crops, whence pollinators of the future?* Lanham, Maryland, Entomological Society of America.

Torchio, P.F. 1985. Field experiments with the pollinator species, *Osmia lignaria propinqua* Cresson, in apple orchards: V (1979–1980), methods of introducing bees, nesting success, seed counts, fruit yields (Hymenoptera: Megachilidae). *J. Kansas Entomol. Soc*. 58: 448–464.

US International Trade Commission. 2010. *Apples*. Industry and Trade Summary. Office of Industries Publication, ITS-04. (Availabe at: http://www.usitc.gov/publications/332/its_4.pdf).

US International Trade Commission. 2011. *China's agricultural trade: competitive conditions and effects on US exports*. USITC Publication, 4219.

Valdovinos-Núñez, G.R., Quezada-Euán, J.J.G., Ancona-Xiu, P., Moo-Valle, H., Carmona, A. & Sánchez, E.R. 2009. Comparative toxicity of pesticides to stingless bees (Hymenoptera: Apidae: Meliponini). *Journal of Economic Entomology*, 102(5), 1737-1742.

Van Heemert, C., De Ruijter, A., Van den Eijnde, J, & Van der Steen, J. 1990. Year-round production of bumble bee colonies for crop pollination. *Bee World*, 71(2): 54-56.

Vaughan, M., Shepherd, M., Kremen, C. & Black, S.H. 2007. *Farming for bees*. Portland, OR, The Xerces Society for Invertebrate Conservation. 34 pp.

Velasco, R., Zharkikh, A., Affourtit, J., Dhingra, A., Cestaro, A., Kalyanaraman, A., Fontana, P., Bhatnagar, S.K., Troggio, M., Pruss, D., Salvi, S., Pindo, M., Baldi, P., Castelletti, S., Cavaiuolo, M., Coppola, G., Costa, F., Cova, V., Dal Ri, A., Goremykin, V., Komjanc, M., Longhi, S., Magnago, P., Malacarne, G., Malnoy, M., Micheletti, D., Moretto, M., Perazzolli, M., Si-Ammour, A., Vezzulli, S., Zini, E., Eldredge, G., Fitzgerald, L.M., Gutin, N., Lanchbury, J., Macalma, T., Mitchell, J.T., Reid, J., Wardell, B., Kodira, C., Chen, Z., Desany, B., Niazi, F., Palmer, M., Koepke, T., Jiwan, D., Schaeffer, S., Krishnan, V., Wu, C., Chu, V.T., King, S.T., Vick, J., Tao, Q., Mraz, A., Stormo, A., Stormo, K., Bogden, R., Ederle, D., Stella, A., Vecchietti, A., Kater, M.M., Masiero, S., Lasserre, P., Lespinasse, Y. Allan, A.C., Bus, V., Chagné, D., Crowhurst, R.N., Gleave, A.P., Lavezzo, E., Fawcett, J.A., Proost, S., Rouzé, P., Sterck, L., Toppo, S., Lazzari, B., Hellens, R.P., Durel, C., Gutin, A., Bumgarner, R.E., Gardiner, S.E., Skolnick, M., Egholm, M., Van de Peer, Y., Salamini, F. & Viola, R. 2010. The genome of the domesticated apple (*Malus x domestica* Borkh.). *Nature Genetics*, 42(10), 833-839.

Verma, L.R. & Dutta, P.C. 1986. Foraging behaviour of *Apis cerana indicia* and *Apis mellifera* in pollinating apple flowers. *J. Apic. Res*., 25: 197-201.

Verma, L.R. & Partap, U. 1993. The Asian hive bee, *Apis cerana*, as a pollinator in vegetable seed production. Kathmandu, Nepal, ICIMOD.

Vicens, N. &. Bosch, J. 2000. Pollinating efficacy of *Osmia cornuta* and *Apis mellifera* (Hymenoptera: Megachilidae, Apidae) on 'Red Delicious' apple. *Environ. Entomol*., 29: 235–240.

Visser, T. & Verhaegh, J.J. 1987. The dependence of fruit and seed set of pear and apple on the number of styles pollinated. *Gartenbauwissenschaft*, 52: 13–16.

Ward, D.L., Marini, R.P. & Byers, R.E. 2001. Relationships among day of year of drop, seed number, and weight of mature apple fruit. *HortScience*, 36:45–48.

Waser, N.M. 1986. Flower constancy: definition, cause, and measurement. *Amer. Nat*., 127: 593-603.

Waser, N.M. & Ollerton, J., eds. 2006. *Plant-pollinator interactions: from specialization to generalization*. Chicago, IL, USA, University of Chicago Press. 488 pp.

Watson, J.C., Wolf, A.T. & Ascher, J.S. 2011. Forested landscapes promote richness and abundance of native bees (Hymenoptera: Apoidea: Anthophila) in Wisconsin apple orchards. *Environ. Entomol.*, 40(3), 621-632.

Weberling, F. 1989. *Morphology of flowers and inflorescences*. New York, Cambridge University Press.

Westwood, M.N. 1978. *Temperate zone pomology*. San Francisco, W.H. Freeman and Co.

Whitehorn, P.R., O'Connor, S., Wackers, F.L. & Goulson, D. 2012. Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science*, 336(6079): 351-352.

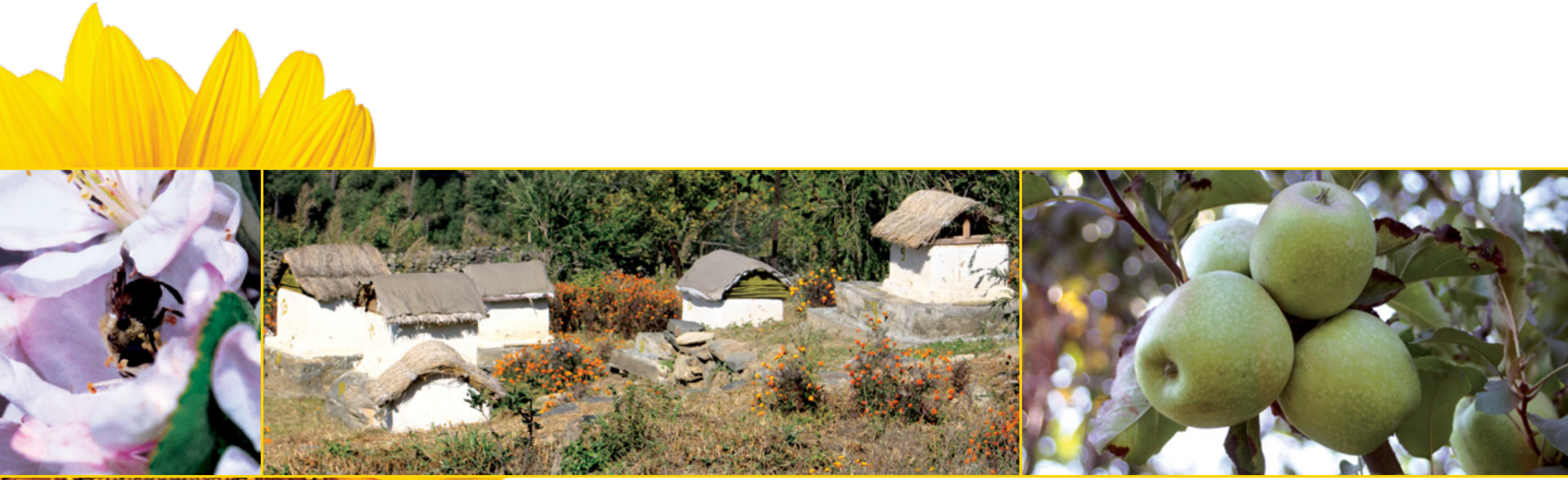
Willmer, P.G. 1986. Foraging patterns and water balance: problems of optimization for a xerophilic bee, *Chalicodoma sicula*. *J. Animal Ecol.*, 55(3): 941-962.

Willmer, P.G. 1988. The role of insect water balance in pollination ecology: *Xylocopa* and *Calotropis*. *Oecologia*, 76(3): 430-438.

Zohary, D. & Hopf, M. 2000. *Domestication of plants in the Old World*. Third Edition, Oxford, UK, Oxford University Press.

The purpose of this manual is to improve knowledge concerning the management of bee pollinators in apple orchards so as to enhance apple quality and yield. The publication was prepared as part of the GEF supported project "Conservation and Management of Pollinators for Sustainable Agriculture, through an Ecosystem Approach" implemented in seven countries – Brazil, Ghana, India, Kenya, Nepal, Pakistan and South Africa.

The project is coordinated by the Food and Agriculture Organization of the United Nations (FAO) with implementation support from the United Nations Environment Programme (UNEP).



GLOBAL ACTION ON **POLLINATION SERVICES**
FOR **SUSTAINABLE AGRICULTURE**

Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla,
00153 Rome, Italy

www.fao.org/pollination
www.fao.org/agriculture/crops/agp-home
e-mail: GlobalAction-Pollination@fao.org

I5527E/1/03.16